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THESIS

AN EVALUATION OF SEA-BASED SUSTAINMENT OF FORCES

by

Christopher M. Frey

September 2000

Thesis Advisor: David A. Schrady
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Amateurs discuss strategy,
Professionals study logistics
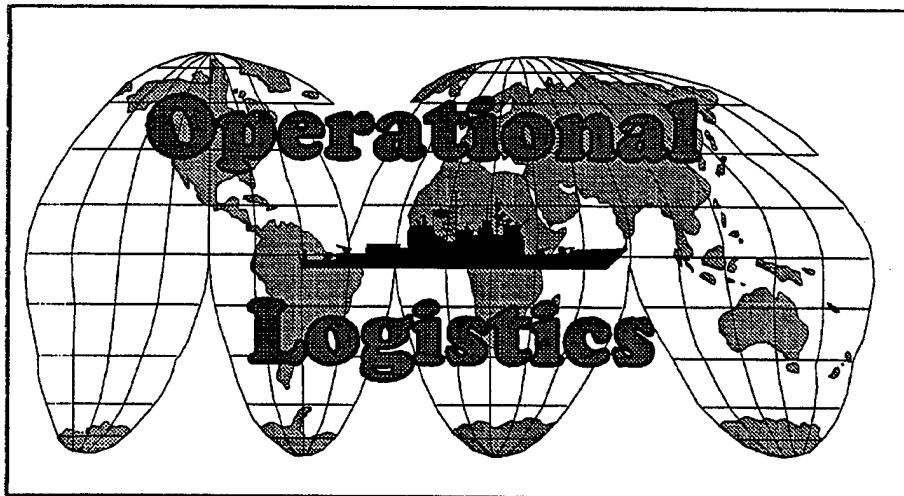
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13. ABSTRACT

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AN EVALUATION OF SEA-BASED SUSTAINMENT OF FORCES

Christopher Mark Frey
Captain, United States Marine Corps
B.S., United States Naval Academy, 1994

Submitted in partial fulfillment of the
requirements for the degree of

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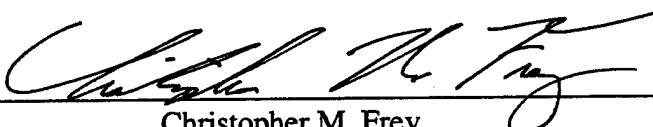
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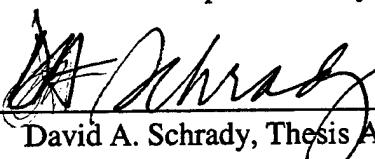
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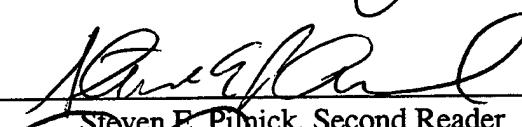
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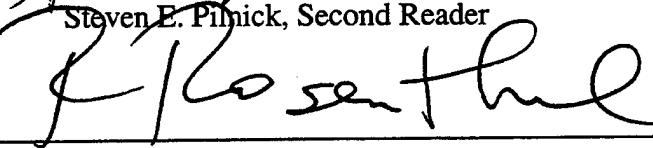
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This thesis models the sea-based sustainment of Marine Expeditionary Brigade (MEB) forces deployed from amphibious warfare ships. A scenario for analysis is developed with force packages of personnel and equipment located at certain locations ashore during different days of an operation. Sustainment requirements and available transporter capacity are then determined and compared for twenty-seven cases comprising different ship-to-shore distances, different levels of aircraft attrition due to enemy interdiction, and different footprints of mobile logistics forces deployed ashore. This comparison provides insight into the ability of SBL to sustain forces ashore conducting operations in accordance with OMFTS and STOM concepts.

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DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the planner.

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LIST OF SYMBOLS, ACRONYMS AND/OR ABBREVIATIONS

AAAV	Advanced Assault Amphibious Vehicle
ACE	Aviation Combat Element of a MAGTF
amphib	Amphibious shipping
AOR	Area of Responsibility
ARG	Amphibious Readiness Group
ATF	Amphibious Task Force
CAS	Close Air Support
DOS	Days of Supply
FARP	Forward Arming and Refueling Point
gal	Gallon
GAMS	General Algebraic Modeling System
GCE	Ground Combat Element of a MAGTF
LAR	Light Armored Reconnaissance
LAV	Light Armored Vehicle
LHA	Amphibious Assault Ship (General Purpose)
LHD	Amphibious Assault Ship (Multipurpose)
LPD	Amphibious Transport Dock
LPF	Logistics Planning Factor
LSD	Dock Landing Ship
LVS	Logistics Vehicle System
MAGTF	Marine Air Ground Task Force
LZ	Landing Zone
MCCDC	Marine Corps Combat Development Command
MEB	Marine Expeditionary Brigade
MEDEVAC	Medical Evacuation
MEU(SOC)	Marine Expeditionary Unit, Special Operations Capable
MIP	Mixed Integer Program
MRE	Meal Ready To Eat
nm	Nautical Mile
OMFTS	Operational Maneuver From The Sea
OTH	Over The Horizon
S&A	Studies and Analysis Division
STOM	Ship-to-Objective Maneuver
SBL	Sea-based Logistics
TBFDS	Tactical Bulk Fuel Distribution System
TBM	Theater Ballistic Missile

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EXECUTIVE SUMMARY

The Marine Corps has formed a vision of how to conduct future amphibious warfare through its development of Operational Maneuver From The Sea (OMFTS), Ship-to-Objective Maneuver (STOM), and Sea-based Logistics (SBL) concepts. These concepts treat the sea as a maneuver space and have forces deploying directly from ship to objectives ashore. By sea-basing command and control, logistics, and some of the fire support functions, a reduction of the landing force's footprint ashore will be achieved along with its advantage of a reduction in logistical requirements and an increase in ground unit mobility. These concepts envision that the combat forces operating ashore will be sustained directly from a sea-base with support from ship-to-shore transporters.

This transition to basing logistics functions upon the sea, however, translates into a greater demand upon these transporters. Air and/or surface transporters could deliver sustainment. However, surface delivery involves opening, re-opening, or maintaining a beachhead and interior lines of communication to the forces operating ashore and starts to move away from the pure concepts of OMFTS and STOM. The transporters desired to support the majority of logistics demand will be the aircraft organic to amphibious warfare ships. If aircraft cannot provide the necessary lift to deliver all required sustainment, the preference to employ LCAC sorties delivering sustainment would be to have these deliveries take place during the later periods of the operation, with the fewest number of sorties possible, and to support forces in areas that are the closest to the LCAC landing sites.

The capability of transporters to deliver sustainment to forces operating ashore will be affected largely by ship-to-shore distances, transporter attrition due to enemy interdiction, and the footprint of supplies initially deployed ashore. Planners and decision makers require a means to gauge potential limitations for sea-base sustainment by observing the effects these 3 factors have upon the transporters capability to deliver sustainment to the forces ashore.

This thesis models the sea-based sustainment of Marine Expeditionary Brigade (MEB) forces deployed from amphibious warfare ships. A scenario for analysis is developed with force packages of personnel and equipment located at different locations

ashore during certain days of an operation. Sustainment requirements are determined using both Marine Corps logistics planning factors (LPFs) and assumptions. The expected availability and capability of transportation assets are determined through assumptions regarding maintenance readiness, dedication to missions other than sustainment, and performance characteristics. Three different levels of ship-to-shore distances (long, medium, short), aircraft attrition due to enemy interdiction (high, medium, none), and footprints of mobile logistics forces deployed ashore (heavy, light, none) are determined to provide a wide variation of case studies. This analysis then models the number of CH-53, MV-22, and LCAC sorties per day required to deliver sustainment ashore for each day of the operation. The model's objective function both minimizes the number of LCAC sorties required and, in the event that LCAC sorties are required, attempts to use these sorties to deliver sustainment to areas that have the shortest distance to the LCAC landing site. Observing information that entails the total number of LCAC sorties required for the entire operation, the day on which LCAC sorties are first required, and areas ashore that require support from LCACs helps compare the case studies to one another. Comparing these case studies provides insight into the capability of ship-to-shore transporters to support the SBL concept. These comparisons include some excursions that tests the transporters capability by further increasing the levels of attrition due to enemy interdiction. Overall, the analysis demonstrates potential limitations for sea-based sustainment.

This analysis reveals that delivering sustainment with aircraft alone can be accomplished for all case studies where ship-to-shore distances are either short or medium as defined herein. Delivery of sustainment for all case studies that include long ship-to-shore distances can only be accomplished with support from LCAC sorties. In these case studies, however, the total number of LCAC sorties required to support the entire operation are reduced considerably by deploying a mobile logistics force as opposed to not deploying one, when aircraft attrition is relatively low. The day on which LCAC sorties are first required is also pushed back much further into the operation when deciding to deploy a mobile logistics force ashore. Because a larger size force will consume a greater quantity of supplies, deploying a heavy footprint of mobile logistics

forces does not reduce the total number of LCAC sorties by much, when compared to a light footprint. The heavy footprint, however, will delay the day on which LCAC sorties are first required by a day or more.

Comparing results from these case studies can help planners and decision makers become more aware of the effects that factors they have control over, such as deploying logistics forces ashore and maintaining certain ship-to-shore distances, and factors they have less control over, such as the enemy's capability to attrite friendly aircraft, have upon the capability to deliver sustainment in accordance with SBL.

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I.   INTRODUCTION

The Concepts Division of the Marine Corps Combat Development Command (MCCDC), through its development of the *United States Marine Corps Warfighting Concepts for the 21st Century* [Ref. 1], has formed a vision of how the Marines Corps will fight in future campaigns. The cornerstones of these concepts are Operational Maneuver from the Sea (OMFTS), Ship to Objective Maneuver (STOM) and Sea-based Logistics (SBL).

OMFTS describes how the United States Marine Corps and United States Navy will conduct future power projection operations. The main advantage that OMFTS provides is its generation of overwhelming tempo and momentum against the enemy by focusing on operational objectives while using the sea as a maneuver space [Ref. 2]. A key concept in OMFTS is reducing the footprint of the landing force by sea-basing command and control, logistics, and some of the fire support functions. With a reduction of the landing force's footprint also comes the advantage of both a reduction in logistical requirements and an increase in ground unit mobility.

STOM is the concept for implementing OMFTS at the tactical level. STOM seeks to exploit advances in mobility, communications, navigational systems, and precision munitions by providing the commander the capability to maneuver combat forces seamlessly from over the horizon at sea to operational objective areas ashore [Ref. 3]. Deployment of forces will take place through vertical and/or surface means. However, landing forces will no longer have the requirement of securing the beach, which has an associated operational pause. Instead, the landing force will generate overwhelming tempo and over match enemy weakness with its power, surprise, and swift execution [Ref. 3]. "By requiring the enemy to defend a vast area against our sea-borne mobility and deep power projection, naval forces will render most of his force irrelevant." [Ref. 3]

The SBL concept describes the operational and tactical logistical support of forces operating ashore in accordance with both the OMFTS and STOM concepts. The primary focus of SBL is the sea basing of logistics functions to reduce or eliminate the logistics footprint ashore historically used in amphibious operations. By locating most if not all logistics functions on the sea, the combat service support (CSS) forces have the advantage

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of concentrating more on supporting the warfighter without dedication of resources to support rear area security, a concern inherent in traditional shore-based logistics operations. Instead of vast quantities of material (much of which may be of little use) being pushed forward, tactical units will communicate consumption data that will pull tailored support to maneuver units [Ref. 4]. Requirements for SBL include total asset visibility, selective off-load capability, an effective command and control system, and the systems for delivering CSS from the ship to the force(s) ashore.

This transition to basing logistics functions upon the sea, however, translates into a greater demand upon ship-to-shore transporters. Sustainment could be delivered ashore by air and/or surface transporters. Surface delivery involves opening/reopening/or maintaining a beachhead and interior lines of communication to the forces operating ashore [Ref. 5]. Further, tactical decisions to deliver sustainment via surface means will start to move away from the pure concepts of OMFTS and STOM. The transporters that will supply the majority of logistics demands will be the aircraft organic to amphibious warfare ships (amphibs) of the sea-base. Daily deliveries of water, rations, fuel and ammunition to the forces ashore will makeup the majority of logistics support missions for these aircraft.

The ability of aircraft to deliver sustainment is constrained by aircraft readiness for sustainment missions, payload capacities, and maximum number of daily sorties, among other things. Aircraft readiness for sustainment missions is a function of maintenance readiness, combat attrition, and aircraft dedication to other missions. Aircraft payloads depend on aircraft type, commodity being transported, the distance to the forces ashore from the sea-base, mode of carry (internal or external), and environmental conditions. The maximum number of daily sustainment sorties per aircraft depends on maximum crew operational hours, aircraft speeds, and the distance from the sea-base to the forces ashore.

In operations involving OMFTS and STOM scenarios, moving the sea-base further over the horizon and away from the shoreline may be required for protection of amphibs from enemy anti-ship missiles. Tactical decisions to move the sea-base further away from the shore will lengthen distances to the forces operating ashore and result in decreasing both aircraft payload and maximum number of daily sorties. Therefore, an increase in

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enemy threat to amphibs corresponds to a decrease in the ability to deliver sustainment via aircraft.

Tactical decisions to deploy logistics vehicles carrying sizable quantities of commodities ashore with the landing force would decrease the amount of sustainment required for delivery by aircraft sorties. These decisions, however, would increase the footprint of forces ashore, possibly slow down momentum, and require some resources dedicated to security of logistics vehicles.

Planners and decision makers require a means to gauge potential limitations for sea-based sustainment by observing the effects of previously mentioned tactical decisions. The purpose of this thesis is to provide insight to military planners of what effects tactical/operational decisions have on the Amphibious Task Force's (ATF) ability to sustain forces ashore from a sea-base. This thesis will model sea-based sustainment within a scenario involving elements of a Marine Expeditionary Brigade (MEB) operating ashore. The scenario used for this analysis was provided for by the Studies and Analysis Division (S&A) of MCCDC [Ref. 6].

II.   BACKGROUND

A.   RECENT STUDIES

Recent studies from officers in the Operational Logistics curriculum at the Naval Postgraduate School have focused on the limitations of SBL resulting from transportation support. In 1997, LT Mark Beddose focused his studies on Marine Expeditionary Unit (Special Operations Capable) (MEU(SOC)) forces, while computing the maximum feasible ship-to-objective distances for operating aircraft sustainment missions [Ref. 7]. He stated that amphibs would desire to be located at least 100 nm from enemy shores due to the threat of anti-ship missiles, mines, diesel submarines, and small coastal craft. His model allowed for attrition of aircraft over time and as such showed how ship-to-objective distances would shrink, the longer sustainment missions continued. LT Beddose's analysis showed that anticipated future aircraft can support small infiltration type units but cannot support a traditional ground force mix at the ship-to-shore distances envisioned.

In 1998, Major Robert Hagan examined the feasibility of sustaining elements of a MEU(SOC) from a sea-base over a range of standard MEU(SOC) missions [Ref. 8]. He determined the people and equipment, together a force package, required for each mission. He then determined, using standard planning factors, each force package's sustainment requirements. By translating a force package's sustainment calculations into a demand for aircraft sorties, he demonstrated the degree to which a MEU(SOC)'s limited aircraft inventory will be able to meet requirements if sustainment is delivered exclusively via aerial means.

In comparison to previous studies, this analysis uses similar discrete modeling to develop sustainment requirements for the forces ashore. Other similarities include observing the effects of aircraft attrition and the movement of ship-to-objective distances upon the capability to deliver sustainment with aircraft. This study differs, however, with the focus on supporting a much larger size force ashore, having a requirement to sustain tactical aircraft ashore, having a requirement to deliver sustainment to forces located in more than one location, and by observing the effects of deploying logistics vehicles upon the ability to sustain forces ashore.

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B. SHIP TO SHORE TRANSPORTERS

The transporters that will support ship to shore movement in future ATF campaigns are a combination of rotary-wing aircraft and surface craft.

1. MV-22

The MV-22 Osprey is the Marine Corps replacement for the CH-46E and CH-53D medium lift assault helicopters. The MV-22 is the Marine Corps version of a tilt-rotor aircraft, which can take-off and land vertically like a helicopter, then fly like an airplane. Using tilt rotor technology, this aircraft will be able to travel further, at much higher speeds and with a much larger payload than the fleet of aircraft that it is replacing. The MV-22 has not been introduced to the fleet yet, but is envisioned to be fully operational by 2010. The following are tasks that the MV-22 will be able to perform:

- Positioning/repositioning tactical forces from ship to shore

- Support the distribution of supplies

- Provide a command and control platform

- Casualty evacuation

- Tactical Recovery of Aircraft and Personnel (TRAP)

The MV-22 will provide an enhanced capability of personnel deployment with its 200+ knots speed. With regard to movement of external loads, the MV-22 will not provide a great speed advantage since its speed, in this case, will be constrained by the load's profile. MV-22 deliveries of cargo will be accomplished via external means due to internal constraints of cabin dimensions and cargo floor weight limitations.

2. CH-53E

The CH-53E Super Stallion is the Marine Corps heavy transport helicopter. Tasks for the CH-53E include those listed for the Osprey, however, the CH-53E is mostly utilized for its ability to externally lift heavy oversized equipment. The CH-53E is also used tactically for its capability to position/reposition artillery units in support of reducing

the effects of enemy counter-battery fires. It can move more personnel and possesses a greater payload capacity than the Osprey but cannot match the Osprey's speed when the MV-22 has an internal load.

The CH-53 provides an enhanced capability to transport fuel when using the internally loaded Tactical Bulk Fuel Distribution System (TBFDS). The TBFDS is a three tank, air transportable, fuel-delivery, forward area refueling, and range-extension system. It consists of four subsystems: three 800-gallon fuel tanks, a restraint system, an electrical fuel control panel, and a two point dispensing system. The dispensing system is capable of pumping 120 gallons per minute and a 200-foot separation between the host aircraft and the receiving aircraft or vehicle [Ref. 9]. The TBFDS allows CH-53s to transport and dispense fuel to aircraft or vehicles at Forward Arming and Refueling Points (FARP) ashore. The CH-53E with TBFDS supports the over-the-horizon refueling requirement contained in the OMFTS concept.

3. Landing Craft Air Cushion (LCAC)

The LCAC employs air cushion vehicle technology with gas turbine propulsion making it a high speed, over-the-beach landing craft that can deliver a 60–75 ton payload from ships well over the horizon (e.g. > 25 nautical miles (nm)). It is used now to transport personnel, weapon systems, vehicles, and cargo from ship-to-shore across the beach. The LCAC will be the preferred landing craft for surface transportation of sustainment in an OMFTS scenario.

4. Advanced Amphibious Assault Vehicle (AAAV)

The AAAV is the replacement for the AAV. It is not currently in the fleet but is envisioned to be at its full operating capability by 2012. The AAAV is a light armor protected personnel carrier that transports the surface assault elements from amphibs to objectives ashore. Once ashore, the AAAV supports mechanized operations through improved infantry mobility and direct fire support that will destroy antitank weapons, bunkers or dismounted infantry, etc. It will posses capabilities that will more than double the AAV speeds on both water and on land. The AAAV's increased range over the AAV

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enables it to have an over the horizon capability, one of the characteristics inherent in the OMFTS concept.

The AAAV is not a transporter of sustainment, however. While the AAAV is a highly capable platform, the internal "cube" of the vehicle prohibits it from carrying large amounts of sustainment to forces ashore and with its impressive firepower it will be classified as an operational tool that the landing force commander will not likely commit to logistics duties [Ref. 10].

C.   DAILY SUSTAINMENT REQUIREMENTS

The daily sustainment requirements of the ground forces ashore are functions of the deployed number of personnel, number and types of equipment, number and types of weapon systems, and the events taking place ashore. Sustainment requirements are determined by respective classes of supply [Ref. 8]. The classes of supply are:

- I   Subsistence (MREs and Water)

- II   Individual Equipment

- III   Petroleum, Oils, and Lubricants

- IV   Construction Materials

- V   Ammunition (W-Ground, A-Aviation)

- VI   Personal Demand Items

- VII   Major End Items

- VIII   Medical Supplies

- IX   Repair Parts

- X   Non-Military Program Material

Of the classes of supply, this thesis concentrates on the sustainment requirements of Class I, Class III, and Class V. The material comprising Class I, Class III, and Class V

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are the largest, by weight and volume, and most challenging to move with air and surface transportation assets [Ref. 11].

This analysis uses Marine Corps Logistics Planning Factors (LPFs) published in the Marine Air Ground Task Force (MAGTF) Data Library (MDL) [Ref. 12] to model Class I, Class III, and Class V (W) requirements for the ground forces operating ashore. This analysis further categorizes requirements into commodities of rations (MREs), water, fuel, and ammunition. For rations and ammo, the weight that must be carried is calculated and for water and fuel the number of gallons that must be carried is calculated. Rations and ammunition movement via aircraft is accomplished externally in nets carrying pallets, while fuel and water movement is accomplished externally in bladders. Rations and ammunition movement via landing craft is accomplished by loading logistics vehicles with pallets of commodities, while fuel and water movement is accomplished by loading logistics vehicles carrying bulk liquid containers.

Daily sustainment requirements of the Marine Corps tactical aircraft operating ashore are functions of number and types of tactical aircraft, number of sorties per aircraft, and ordnance payload of each aircraft. Tactical aircraft will require ammunition, fuel, and water sustainment support. There are no useful LPFs for tactical aircraft and therefore the determination of these aircrafts' sustainment requirements is accomplished through many assumptions. The scenario establishes the number and types of tactical aircraft employed. In accordance with the scenario, missions are assigned to the respective aircraft as well as an average number of daily sorties. Through the assignment of aircraft missions and discussions with personnel knowledgeable of these aircraft, ordnance payloads and LPFs detailing percentage of ordnance per sortie-mission, average fuel use per aircraft sortie, and average water use per aircraft sortie are developed [Refs. 13 and 14]. Tactical aircraft are re-supplied at the Forward Arming and Refueling Point (FARP) when operating ashore. Ammunition and water are transported ashore to the FARP by the same means as they are delivered to ground forces, while fuel is transported to the FARP via CH-53 using the TBFDS.

III. APPROACH

The first step in the approach is to obtain and develop a scenario that contains forces fighting ashore and consuming commodities, a sea-base of amphibs, a make up of ship-to-shore transporters, distances from the sea-base to forces ashore and a duration of the operation. This thesis uses a scenario drawn largely from one developed at the Studies and Analysis Division (S&A) of MCCDC [Ref. 6]. The scenario contains data and background information pertaining to elements of a MEB conducting an amphibious assault.

The second step is to determine the factors to make variable within the study. This supports the development of different case studies for comparison and contrast. The factors that are varied in this study are based upon the enemy's capability to interdict both ships and transporters, the courses of action dealing with the use of logistics vehicles to support forces operating ashore, and how far away to operate the sea-base from the forces ashore.

A. SCENARIO

1. Situation/Mission

A vital sea-line of communication has been mined by an enemy nation in the year 2011(refer to figure 1). This enemy nation has anti-ship missile and theater ballistic missile (TBM) capabilities. The mission of this scenario is to deny the enemy the ability to launch their TBMs and anti-ship missiles from within a certain coastal area (90 nm by 15 nm). This area must be controlled in support of naval forces accomplishing their mission of clearing mines and reopening the sea-lane (a strait). This requires locating and destroying fixed missile sites and mobile launchers operating in the area of responsibility along the coast. This mission is to be carried out by an Amphibious Task Force (ATF) comprised of a forward-deployed MEU and an Amphibious MEB deploying with east coast naval forces. The ATF mission is expected to last (14) days upon commencement of D-day. The meteorological condition in theater has the temperature at 105°F and humidity at 83%. The total number of personnel operating ashore is over 4,250 and the elevations inland are 500 feet above sea level. [Ref. 6]
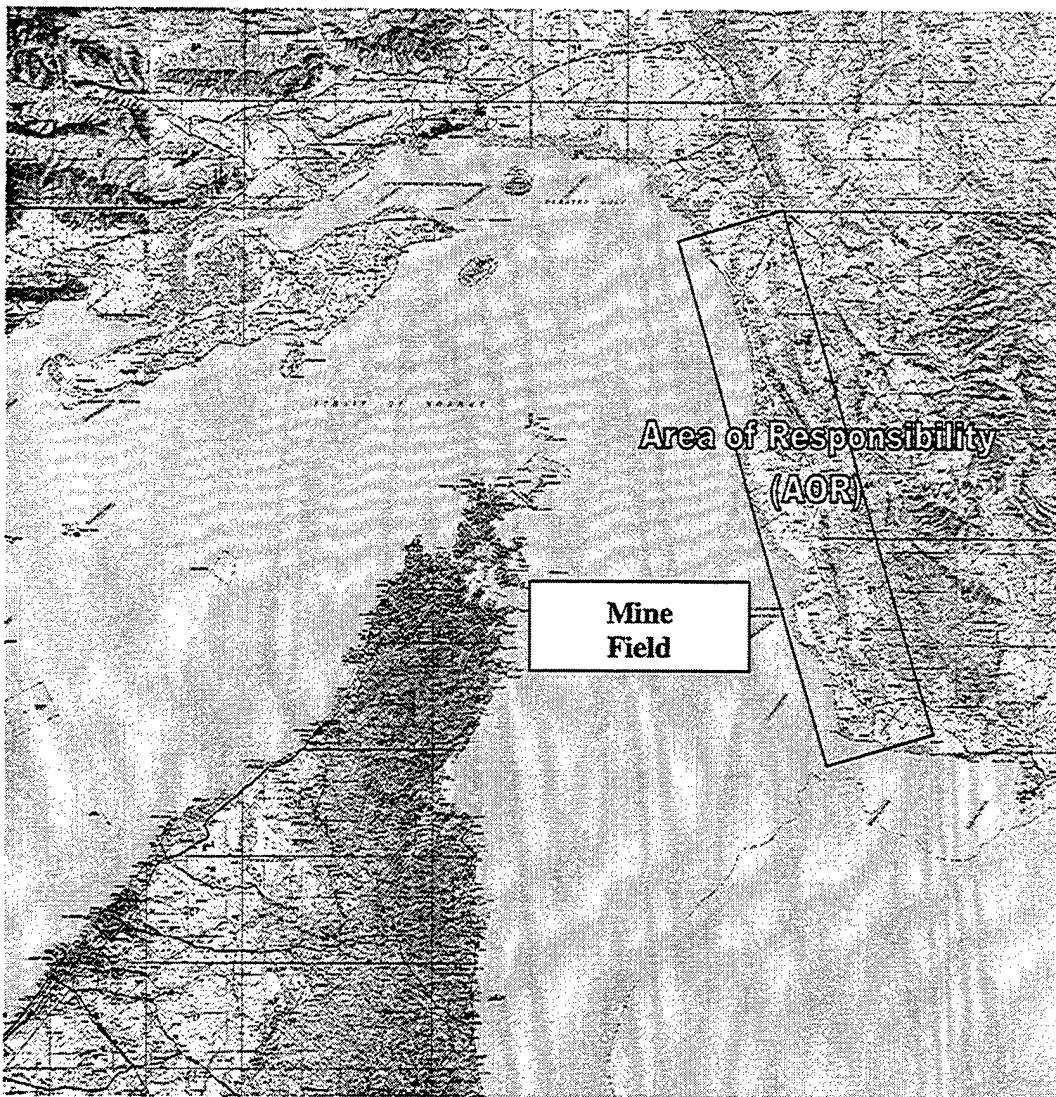
Figure 1. Theater of Operations

2.   Scheme of Maneuver

Amphibs maneuver within 25 nm of the area of responsibility (AOR). Naval ships operate under an AEGIS umbrella and are supplemented by an improved-self defense capability. One Battalion Landing Team (BLT) (3 infantry companies and an artillery battery) is inserted vertically into area of operation 1 (refer to Figure 2 for area of operation). The northern BLT seizes missile-firing facilities and establishes a blocking position to prevent enemy forces from entering the AOR. Two BLTs conduct surface landings in the south of the AOR (25 nm from the sea-base and located to the west of area of operation 8). Once ashore one BLT (with artillery battery and combat engineer

platoon) moves by AAAV to initial blocking positions in the south, oriented east (area of operation 8). The other mechanized BLT(-), reinforced with a tank company, will maneuver northwest to destroy any enemy missile sites in the AOR. It will conduct a link-up with the northern BLT to reinforce the northern blocking position (also to deliver the prime movers to the howitzers that were inserted vertically). Two Light Armor Reconnaissance (LAR) companies (landing with the BLTs) will maneuver separately through the AOR (from the south to the north) to seek out and destroy enemy mobile TBMs and anti-ship missiles for a period of 4 days. Upon completion of the seek and destroy mission, the LAR companies will conduct a link up with the northern positioned BLTs.

A Mobile (20 vehicles) Forward Arming and Refueling Point (Mobile FARP) unit will phase ashore with the last surface landings. Once ashore, the Mobile FARP moves north to a location beyond threat artillery range and in an area that can be easily secured. The Mobile FARP is established ashore to support the AH-1Zs and AV-8Bs with fuel, ammunition and water. The Mobile FARP will help these aircraft to operate with minimal turn around time and help open ship flight deck space for logistics support flights.
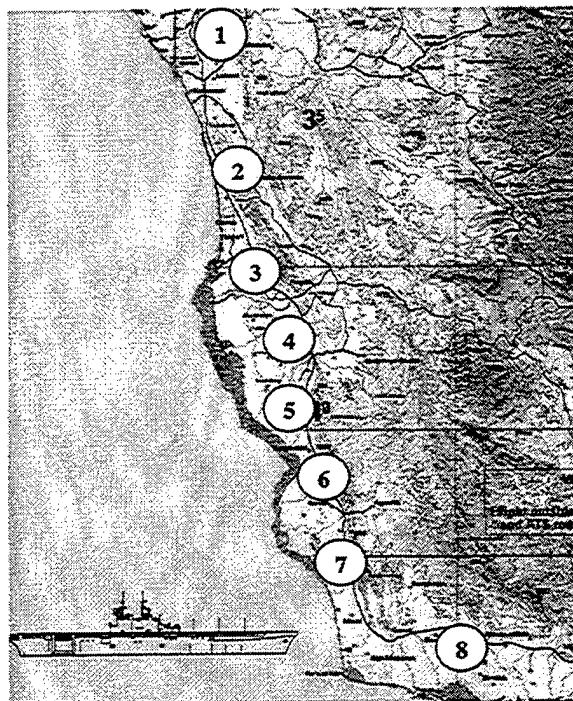
Figure 2. Areas of Operation Ashore (from Ref. 6)

3.   Ships/Transporters

Table 1 lists the specific ships that make up the sea-base and also details the transporter types and respective quantities that are maintained on each ship. The information regarding transporters maintained per ship is taken from the scenario [Ref. 6].

SHIP	LCAC	LCU	MV-22	CH-53
LHA-5	1	2	12	6
LHD-1	2	0	12	6
LHD-3	2	0	12	6
LHD-5 (MEU)	2	0	12	4
LPD-17	2	0	0	0
LPD-20	2	0	0	0
LPD-24	2	0	0	0
LPD-25 (MEU)	2	0	0	0
LSD-44	2	0	0	0
LSD-45	3	0	0	0
LSD-46	2	0	0	0
LSD-50 (MEU)	2	0	0	0
Total:	24	2	48	22

Table 1. Sea-base Ship and Transporter Make up

4.   Tactical Aircraft

24 AV-8B Harriers self deploy from CONUS with strategic lift support from the Air Mobility Command (AMC) and are shore-based in a nearby host nation. This provides additional space aboard the amphibious ships, a requirement to operate such a large number of transporters. 16 AH-1Z Cobras and 12 UH-1N Hueys are also operating in theater from the amphibious ships.

B. ENEMY CAPABILITY AND OPERATIONAL DECISIONS

With a scenario and forces ashore given, the objective is to evaluate the feasibility of sustaining operations ashore via SBL. The enemy's capabilities and operational/tactical decisions made by the ATF's leadership have a major impact on the ability of the Marines fighting ashore to receive sufficient sustainment from a sea-base. As such, the following topics need to be addressed by planners and decision makers.

1. Level of Enemy Threat to Amphibs

The first question that senior leadership needs to assess is, "What is the level of enemy threat to the amphibs?" Determining whether the threat is high, medium or low should translate into a safe operating distance from the sea-base to the operating forces ashore. An increased enemy threat to the amphibs requires an increase to the standoff distance from the sea-base to the shoreline. For an OMFTS scenario, the minimum distance from ship to shore is over-the-horizon (approximately 25 nm). In this scenario three different sea-base locations are used to reflect a low, medium and high threat level to amphibious ships (refer to figure 3). A low threat to amphibs is analyzed using sea-base # 1, a medium threat is analyzed using sea-base # 2, and a high threat is analyzed using sea-base # 3. All activity on the first day of the operation (e.g. the surface deployment) will take place from the sea-base #1 location.
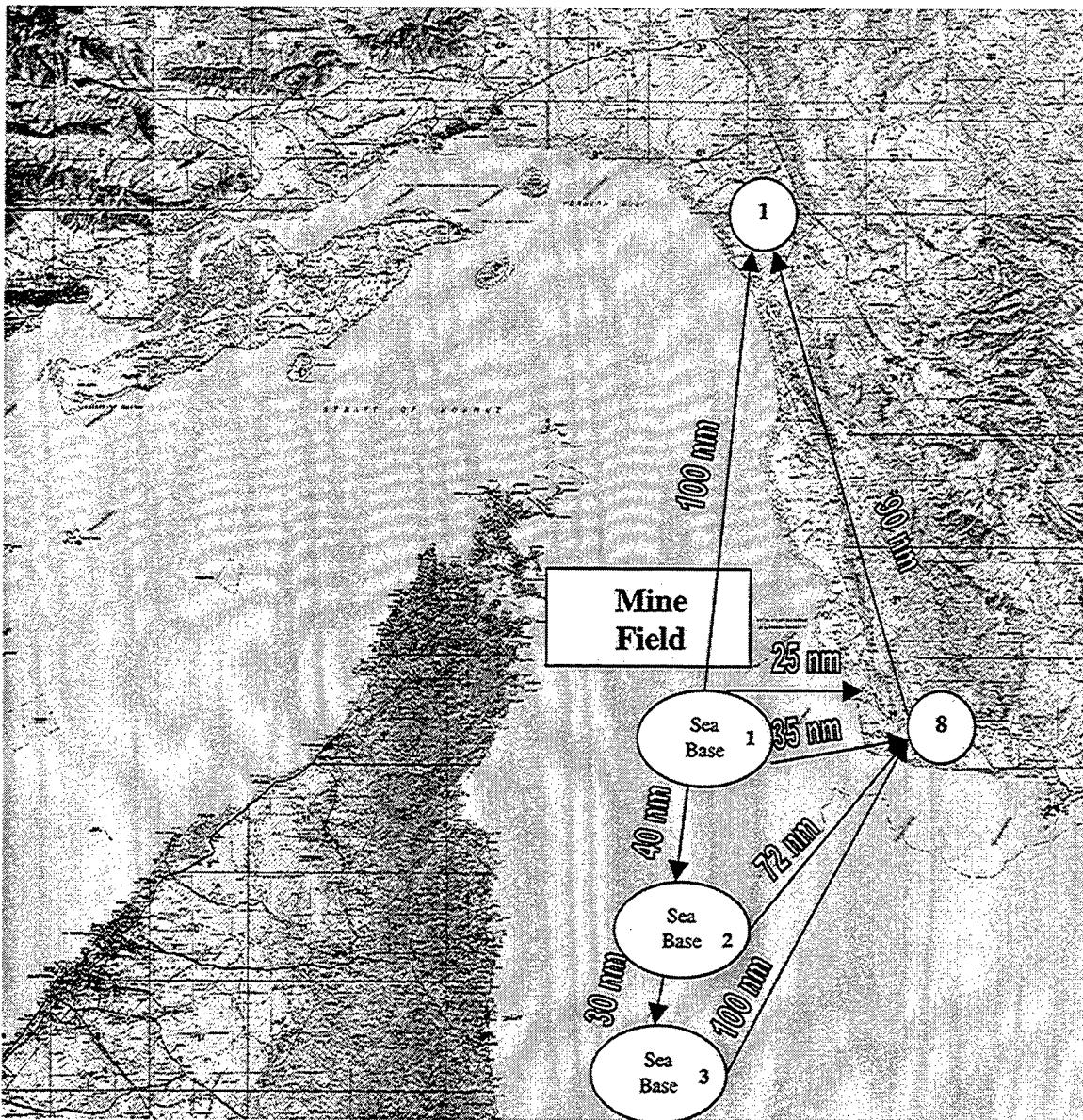
Figure 3. Sea-base Locations

2. Level of Enemy Threat to Friendly Aircraft

The second question that needs to be assessed is, "What is the enemy threat to our aircraft during the operation?" For this study, a high level of threat translates to a high level of aircraft attrition, a medium level threat translates to a medium level of aircraft attrition, and a minimal threat translates to no aircraft attrition. Having this information figures significantly into aircraft availability for support missions.

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3. Addition of Logistics Vehicles to the Landing Plan

The third question that requires determination is, "Can the concept of operations ashore support the addition of logistics vehicles to the landing plan?" Introducing logistics vehicles ashore in the landing plan increases the footprint ashore and as such requires security, increases logistical requirements, and could possibly slow down the pace of operations. On the other hand, not only can these vehicles support forces with commodities initially carried but also can help in overall receipt and distribution of future commodities delivered by aircraft. They also possess a means to store inventory when commodity delivered by aircraft exceeds what is required for use on a certain day. This study examines the following situations with regard to the addition of logistics vehicles into the landing plan:

- A light footprint of logistics vehicles in support of forces located in the northern area. These vehicles will travel north with tactical vehicles on day one.

- A heavy footprint of logistics vehicles in support of forces located in the northern area.

4. Use of Landing Craft for Sustainment Missions

The last set of questions that require assessment are, "Will landing craft be vulnerable to enemy interdiction if used during the entire operation? Will the concept of operations ashore and enemy situation allow ground forces the capability to secure a beachhead and, from the beach, lines of communications ashore?" Yes or no answers to these questions translates into whether the ATF can or cannot employ landing craft for daily re-supply missions. In this scenario, the use of landing craft in support of sustaining forces ashore occur only in the event that aircraft cannot provide all the lift that is required for movement of sustainment. Due to the mine threat, the only beaches that can accommodate the landing craft are in the south of the AOR. If landing craft deliveries of sustainment are required, then there is a desire to have these deliveries be in support of the

southernmost forces, in an attempt to shorten the lines of communication from the beach to the area supported.

C. CASE STUDIES

This thesis models a certain number of case studies, providing information to planners and leadership to compare and contrast. The model's objective function is to minimize the number of LCAC sorties required to transport commodities ashore over the 14-day operation. The ATF's desire in an OMFTS scenario is that aircraft, if feasible, accomplish all ship-to-shore movement of sustainment. This study uses three variables (threat to aircraft, ship-to-objective distances, and deployment of logistics vehicles) to develop 27 different case studies. The following three **"example"** tables provide a format for which all case studies can be presented and compared to one another by observing the number of LCAC sorties required to deliver sustainment.

Enemy Threat to Aircraft	Far Ship to Shore Distance	Medium Ship to Shore Distance	Near Ship to Shore Distance
High	25 LCAC sorties	20 LCAC sorties	10 LCAC sorties
Medium	15 LCAC sorties	10 LCAC sorties	0 LCAC sorties
None	12 LCAC sorties	6 LCAC sorties	0 LCAC sorties

Table 2. No Deployment of Logistics Vehicles

Enemy Threat to Aircraft	Far Ship to Shore Distance	Medium Ship to Shore Distance	Near Ship to Shore Distance
High	20 LCAC sorties	15 LCAC sorties	5 LCAC sorties
Medium	10 LCAC sorties	5 LCAC sorties	0 LCAC sorties
None	7 LCAC sorties	0 LCAC sorties	0 LCAC sorties

Table 3. Light footprint of Logistics Vehicles supporting the Northern Forces

Enemy Threat to Aircraft	Far Ship to Shore Distance	Medium Ship to Shore Distance	Near Ship to Shore Distance
High	5 LCAC sorties	0 LCAC sorties	0 LCAC sorties
Medium	0 LCAC sorties	0 LCAC sorties	0 LCAC sorties
None	0 LCAC sorties	0 LCAC sorties	0 LCAC sorties

Table 4. Heavy footprint of Logistics Vehicles supporting the Northern Forces

Using the output obtained from these example tables, suppose the ATF felt that there was a medium enemy threat to its ships and thus operated at a medium ship-to-shore distance. Also supposed that there was no real enemy threat to friendly aircraft. Then the ATF leadership could anticipate the difference between deploying a light footprint of logistics vehicles ashore and not deploying these vehicles to be a requirement to deliver sustainment with 6 LCAC sorties over the 14-day operation. In this case, while keeping two variables fixed (ship-to-shore distances and enemy threat to aircraft), leadership can make a more informed decision regarding what value a third variable (deployment of logistics vehicles) should take on, by observing the effects their decisions have on the requirement to use LCACs to deliver sustainment ashore.

The purpose of developing these tables is to provide a means to help the ATF Navy and Marine Corps leadership with their decision making process and in their management of risk. Through a comparison and contrast of the 27 different case studies presented, insight should be gained with regard to what the effects of operational decisions and the enemy's capability have upon the employment of SBL in an OMFTS scenario.

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IV. METHODOLOGY

Daily sustainment requirements, transporter capabilities, the logistics vehicles deployed, and aircraft availability must be determined prior to employing the model. The following are the major factors for which assumptions have been made and data have been developed:

A. DAILY SUSTAINMENT REQUIREMENTS

1. Ground Forces

a) Force Structure

In calculating the ground force sustainment requirements, the size of the force and their equipment located in each area of operation, for each day of the scenario must first be determined. This data is taken from a scenario provided by the Studies and Analysis Division (S&A) of the Marine Corps Combat Development Command (MCCDC) [Ref. 6]. These forces are characterized by number of personnel (consumers of both water and rations), vehicle types and respective quantities (consumers of bulk fuel) and weapon system types and respective quantities (consumers of ammunitions). Table 5 provides a general picture of the size and make up of the ground forces ashore.

Area of Operation	People	HMMWV Variants	7-Ton Trucks	Logistics Vehicles and Refuelers	Light Armored Vehicles	Advanced Assault Amphib Vehicles	Tanks & Armored Support Vehicles	Light Weight 155 Howitzers	Combat Breacher Vehicles
1	2,271	119	31	0	0	35	18	12	2
4	232	0	0	0	46	0	0	0	0
7	55	10	6	4	0	0	0	0	0
8	1,727	132	31	0	4	62	0	6	2

Table 5. Case Study with no Logistics Vehicle Support of the Northern Area, on Day 3

b) Determination of Daily Resupply Requirements

Class I (food and water) requirements are a function of the number of people located ashore. Daily MRE requirements are computed and converted to a pounds per day figure using the following equation [Ref. 8]:

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$$M = N * D * P$$

Where M=total daily MRE requirements in pounds

N=number of people ashore

D=daily MRE requirement per person,(3)

P=average weight in pounds of one MRE including packaging

Daily water requirements are determined using the following equation [Ref. 8]:

$$H = N * W$$

Where H=daily water requirements in gallons

N=number of people ashore

W=daily water planning factor in gallons

The value for W provided in [Ref. 8] is 10 gal/day, however, the value for W in [Ref. 15] is 6 gal/day. In this analysis, the average of these two different values, 8 gal/day, is used exclusively.

Ground Combat Element (GCE) class III (fuel) requirements are a function of equipment type and respective quantity. For each item of equipment, a daily requirement is computed based on planning factors for gallons per hour and operating hours per day [Ref. 8]. Fuel requirements are computed using the following equation [Ref. 8]:

$$F = \sum_j X_j * Y_j * E_j$$

Where F=total daily fuel requirements in gallons

X_j=average fuel use in gallons/hour for equipment type j, [Ref.12]

Y_j=average operational hours/day for equipment type j, [Ref. 12]

E_j=number of equipment type j ashore.

Class V (W) (ground ammunition) requirements are a function of ammunition type, weapon type, threat, and the phase of combat [Ref. 8]. Weapon types range from large weapon systems (e.g. tanks, AAAVs, howitzers) to smaller systems (e.g. 60 mm mortars, M-16s, 9MMs). In this analysis a mechanized threat is assumed for area of operation 1 and an infantry threat is used for all other areas. The MDL has data for two phases of combat, assault and sustained. The phase of combat in this analysis is "assault"

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for the first five days of the operation and then "sustained" for the remaining days of the operation. Daily ammunition requirements are computed from the following equation [Ref. 8]:

$$A = \sum_j Q_{ij} * Y_i * V_j \quad \forall i$$

Where A=total daily ammunition requirement in pounds

Q_{ij}=average rounds/day of type i used by weapon type j, [Ref. 12]

Y_i=weight of ammunition type i in pounds, [Ref. 16].

V_j=number of weapon type j ashore

2. Aviation Combat Element (ACE)

Data representing tactical aircraft daily consumption of commodities supported by the FARP comes from assumptions regarding the scenario. Assumptions for ammunition consumption are made using typical ordnance loads for each aircraft per mission type and number of mission sorties. Assumptions for fuel consumption use information regarding fuel capacity and average operational time per sortie.

a) Scenario Information

In this scenario the Harriers are shore based within a nearby host nation. Commencing on day two of the operation, each available aircraft departs the base and proceeds to the vicinity of area of operation 8 (160 nm trip), where they provide close air support (CAS) to the forces fighting at that location. After expending ammunition and before running out of fuel, each Harrier will then proceed to the FARP located 15 nm northwest of area of operation 8. At the FARP, each Harrier receives fuel, ammunition, and water required to maintain operations. From the FARP, each aircraft then proceeds another 75 nm north to the vicinity of area of operation 1 where they provide CAS to the forces fighting at that location. After expending ammunition near area of operation 1, each Harrier then travels another 75 nm back to the FARP, where it again receives fuel, ammunition and water. From the FARP, each aircraft proceeds back to area of operation 8, where they provide CAS for a duration of time prior to traveling back to base.

The Cobras, unlike the Harriers, are based on the amphibs. Each Cobra operates 8 hours a day which is consistent with their operational "crew time" and can

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either be assigned a mission of CAS or escort. Each aircraft's mission dictates their ordnance payload. For this analysis, it is assumed that missions are split evenly between available Cobras. A Cobra can remain in the air for approximately two hours before requiring fuel [Ref. 14]. This equates to 4 fuelings a day and a total of 3 taking place at the FARP.

.   *b)*   *Class III*

Fuel requirements (Class III) are a function of number of aircraft, aircraft types, and number of fuelings required each day at the FARP. This relationship is reflected in the following equation:

$$F = \sum_i A_i * R_i * N_i * X_i$$

Where F=total daily FARP fuel required by tactical aircraft in gallons

A_i=total aircraft in theater of type i

R_i=fraction of aircraft type i that are operationally ready to fly each day, $R_i \varepsilon (0,1)$

N_i=total fuelings required at the FARP per aircraft type i per day

X_i=gallons of fuel provided per fueling of aircraft type i

Information for X_i given from [Refs. 13 and 14] provides the values of 235 gal/Cobra fueling and 985 gal/Harrier fueling. The values of N_i come from assumptions of the scenario and are 2 for each Harrier and 3 for each Cobra.

c)   *Class V (A)*

Class V (A) (aviation ordnance) requirements are a function of number of aircraft, aircraft types, the assigned mission of each aircraft, and daily average number of times that an aircraft will expend its ordnance payload. Daily ammunition requirements are computed using the following equation:

$$O = \sum_i \sum_j A_{ij} * R_i * P_{ij} * \left(E_{ij} - 1\right)$$

Where O=total daily FARP ammunition required by tactical aircraft in lbs

A_{ij}=total aircraft in theater of type i assigned to mission j

R_i= fraction of aircraft type i that are operationally ready to fly each day, $R_i \varepsilon$ (0,1)

P_{ij}=ordnance payload in lbs of aircraft type i assigned to mission j

E_{ij}=daily average number of times an aircraft of type i assigned to mission j expends its ordnance payload, $E_{ij} \geq 1$

Values for P_{ij} were given from [Refs. 13 and 14]. This equation uses E_{ij} starting at 1 because the initial ordnance payload of aircraft is provided by the sea-base or host nation shore-base. The values for E_{ij} come from assumptions made. This analysis assumes that an escort mission will have a lower value than a CAS mission and uses the following values: $E_{Harrier,CAS}$= 2.5, $E_{Cobra,CAS}$= 3.5, and $E_{Cobra,escort}$= 1.5.

d) Class I

Class I (water) requirements are only figured for the Harrier. The Harrier requires 36 gallons of purified water per flight [Ref. 13]. Daily water requirements for tactical aircraft are computed using the following equation:

$$W = A * R * N * X$$

Where W=total daily FARP water required by tactical aircraft in gallons

A=total harriers in theater

R= fraction of aircraft type i that are operationally ready to fly each day, $R_i \varepsilon$ (0,1)

N=number of times per day that Harrier water must be replenished at the FARP per aircraft

X=gallons of water provided per Harrier re-supply

B. MAKE UP OF LOGISTICS VEHICLES ASHORE

This analysis observes the effects of deploying logistics vehicles ashore carrying commodities in support of area of operation 1 (the most northern area). These vehicles will be transported ashore via LCACs on day one of the operation and will travel north with a mechanized BLT(-) to area of operation 1. Moving this additional force ashore translates into additional LCAC sorties and additional time required to complete the deployment of forces. The ATF will always desire to complete the deployment of forces

as quickly as possible so as not to slow down the tempo of operations ashore and thus there exists a trade off with the deployment of these vehicles. This analysis has defined two cases of logistics vehicles deploying ashore. These cases are a light footprint, carrying a one day of supply (DOS) in support of forces within area of operation 1, and a heavy footprint, carrying two DOS in support of forces within area of operation 1. A DOS is determined using the amount of commodities consumed during the assault phase at area of operation 1.

Each logistics vehicle will carry only one type of commodity. Rations will not be carried aboard logistics vehicles due to their generally associated low priority amongst the four commodities (ammunition, fuel, water, and food) and the small fraction of requirements they account for when examining total daily sustainment requirements for marines fighting ashore. The number of LCAC sorties required to deploy these vehicles is determined by the vehicle weight and the weight of the commodities carried by the vehicle. The maximum payload that an LCAC can carry is 120,000 lbs. Therefore, the number of LCAC sorties $>$ $^{\text{weight of commodities (lbs)}}/_{120,000\ \text{(lbs)}}$. Under these assumptions and opinions, the following is determined:

1. Light Footprint

A light footprint will comprise vehicles carrying one DOS of ammunition, fuel, and water for the force located in area of operation 1. This case requires 14 additional LCAC sorties to deliver vehicles ashore on day 1 of the operation and is detailed in Table 6.

Commodity Type	# of LCAC Sorties to Transport	Total Commodity Moved
Water	8	21,024 gallons
Fuel	4	20,000 gallons
Ammunition	2	140,800 pounds

Table 6. Movement of a Light Footprint of Sustainment

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2. Heavy Footprint

A heavy footprint will comprise vehicles carrying two DOS of ammunition, fuel, and water for the force located in area of operation 1. This case requires an additional 28 LCAC sorties to deliver vehicles ashore on day 1 of the operation and is detailed in Table 7. In this case one LCAC sortie transports both a vehicle carrying water and a vehicle carrying ammunition (explanation for non-integer sorties).

Commodity Type	# of LCAC Sorties to Transport	Total Commodity Moved
Water	14.5	40,600 gallons
Fuel	8	40,000 gallons
Ammunition	3.5	246,400 pounds

Table 7. Movement of a Heavy Footprint of Sustainment

C. TRANSPORTERS

1. Cargo Profiles

Data detailing aircraft and landing craft cargo payloads per sortie are developed and indexed by commodity type and area of operation. Distances from the sea-base to areas of operations, packaging of commodities, and the capabilities of transporters will determine this. It is assumed that only one commodity type will be transported per aircraft sortie.

a) Range vs. Payload

The following table illustrates the range vs. payload relationship for each transporter with regards to the effect radius traveled has upon the capability to carry cargo based on weight constraints [Refs. 17 and 18]:

Mission Radius (nm)	MV-22 extern. lift(lbs)	CH-53 extern. lift(lbs)	LCAC lift (lbs)
35	12,118	22,500	120,000
50	11,482	22,100	120,000
72	10,600	21,450	120,000
100	9,362	20,600	120,000
115	8,726	20,150	120,000
140	7,620	19,350	120,000
170	6,394	17,800	120,000

Table 8. Mission Radius vs. Cargo Payloads

b) *Aircraft External Lift Packaging of Commodities*

Aircraft movement of cargo is not only limited by the cargo's weight but is also constrained by the packaging of cargo. Water is transported in 250-gallon bladders. A maximum of 6 bladders can be lifted by a single aircraft [Ref. 19]. As a result of this, a constraint of 1,500 gallons of water (13,890 lbs which includes the weight of bladders) is placed upon the lift capability of one aircraft sortie.

The packaging of food (MREs) and ammunition is accomplished with nets loaded with pallets. Information obtained from [Ref. 15] established that ration weight is 1.46 lbs/MRE and that one pallet provides 1,110 lbs of MREs or alternately provides 2,200 lbs of ammo. This analysis uses a maximum of 16 pallets moved in 8 nets (2 pallets per net) for food movement [Ref. 20]. Therefore, a constraint of 17,760 lbs of MREs is placed upon the lift capability of one aircraft sortie. This analysis does not use a similar pallet constraint with ammunition. This is due to an ammo pallet being approximately twice as heavy as an MRE pallet. Resulting from this, the aircrafts' maximum payload constraint limits an external lift of ammunition before a maximum pallet constraint can.

The packaging of fuel in this analysis is accomplished with 500-gallon bladders. A maximum of 4 bladders can be lifted by a single aircraft [Ref. 19]. As a result of this, a constraint of 2,000 gallons of fuel (14,600 lbs which includes the weight of bladders) is placed upon the lift capability of one aircraft sortie.

To illustrate the effects both the constraints of packaging and weight have upon the MV-22 and CH-53E's capability to deliver commodities, Table 9, based on the above constraints and Table 6, is provided.

Mission Radius (nm)	MV-22 max lift of water (gal)	MV-22 max lift of fuel (gal)	MV-22 max lift of MREs (lbs)	MV-22 max lift of ammo (lbs)	CH-53 max lift of water (gal)	CH-53 max lift of fuel (gal)	CH-53 max lift of MREs (lbs)	CH-53 max lift of ammo (lbs)
35	1,250	1,500	12,118	12,118	1,500	2,000	17,760	22,500
50	1,000	1,500	11,482	11,482	1,500	2,000	17,760	22,100
72	1,000	1,000	10,600	10,600	1,500	2,000	17,760	21,450
100	1,000	1,000	9,362	9,362	1,500	2,000	17,760	20,600
115	750	1,000	8,726	8,726	1,500	2,000	17,760	20,150
140	750	1,000	7,620	7,620	1,500	2,000	17,760	19,350
170	500	500	6,394	6,394	1,500	2,000	17,760	17,800

Table 9. Maximum Load of Commodity per Aircraft Sortie

This analysis transforms the sustainment required ashore into the number of MV-22 sorties required to deliver sustainment. MV-22 sortie requirements are a function of both sustainment per area per commodity and the MV-22 maximum load of commodity per area per sortie. Daily requirements for MV-22 sorties are computed using the following equation:

$$S_{ij} = \left\lceil C_{ij} / M_{ij} \right\rceil \qquad \forall ij$$

Where S_{ij} =the daily requirement for MV-22 sorties carrying commodity i to area j

C_{ij} =the daily sustainment requirement of commodity i at area j in lbs or gal

M_{ij} =the MV-22 maximum load of commodity i delivered to area j per sortie in lbs or gal

In this analysis, CH-53s are employed to accomplish as many MV-22 equivalent sorties as possible. The following table uses information from Table 9 to detail how many MV-22 equivalent sorties a CH-53 can accomplish when delivering a certain commodity to a certain distance ashore:

Mission Radius (nm)	CH-53 max lift of water	CH-53 max lift of fuel	CH-53 max lift of MREs	CH-53 max lift of ammo
35	1.2	1.5	1.466	1.857
50	1.5	1.5	1.547	1.925
72	1.5	2	1.675	2.023
100	1.5	2	1.9	2.2
115	2	2	2.14	2.49
140	2	2	2.33	2.53
170	3	4	2.78	2.78

Table 10. CH-53 Sorties Measured in MV-22 Equivalent Sorties

c) LCAC Movement of Commodities

When LCACs are used to provide sustainment to the forces ashore, it is accomplished by transporting logistics vehicles carrying sizable amounts of commodities. The constraint that dictates how many logistics vehicles can be transported ashore per LCAC is the LCAC's maximum payload capacity of 120,000 lbs.

LCAC movement of water takes place by transporting 2 Logistics Vehicle Systems (LVS) carrying 2 water containers each, with each container having the capacity to hold 900 gallons (1800 gallons per LVS). In order to stay within the LCAC payload weight constraint, each LVS carries 1,400 gallons of water. This equates to 2,800 gallons of water delivered per LCAC sortie.

LCAC movement of fuel takes place by transporting 1 M970 refueler with a capacity to hold 5,000 gallons of fuel. This equates to 5,000 gallons of fuel delivered per LCAC sortie.

LCAC movement of MREs and ammunition take place by transporting 2 LVSs carrying a combination of both commodities. The combination of these commodities is classified as "dry cargo". One LVS can carry 16 pallets of MREs (double stacked on trailer) for a total of 17,760 lbs of MREs per LVS (1,110 lbs per pallet). One LVS can alternatively carry 8 pallets of ammunition (single stacked on trailer) for a total of 17,600 lbs of ammo per LVS (2,200 lbs per pallet). This analysis uses the maximum ammunition weight per LVS for the constraint of 35,200 lbs of dry cargo per LCAC sortie.

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2. Sortie Rates

Sortie rates for each aircraft are a function of the maximum time allowed for operation in a day (referred to as "crew day"), the aircraft type, and the distances to the areas requiring sustainment. The value for "crew day" used in this analysis is 8 hours, which is provided for by fleet standard operating procedures (SOP).

Average aircraft sortie times are determined for each aircraft type and area of operation. This analysis uses a sequence of events to determine these average sortie times [Ref. 15]. The following are the events and their respective completion times listed in the order that they take place:

- Attach external lift (3 minutes)

- Lift and clear sea-base area (2 minutes)

- Movement to area of operation ashore with an external lift (time varies)

- Approach landing zone (LZ) located in area of operation (2 minutes)

- Disengage external lift (3 minutes)

- Clear LZ area (2 minutes)

- Movement to sea-base without an external lift (time varies)

- Approach and land at sea-base (2 minutes)

- Re-fuel at sea-base (15 minutes)

Speeds for the MV-22 and CH-53 differ from one another. The MV-22 can maintain a speed of 110 knots while transporting an external load and 210 knots while transiting back to the sea-base empty [Ref. 18]. The CH-53 can maintain a speed of 100 knots while transporting an external load and 130 knots while transiting back to the sea-base empty [Ref. 15].

Average sortie times are figured using the following equation:

$$S_{ij} = P + L + (D_j * 60) / SL_i + Z + O + C + (D_j * 60) / SE_i + A + R$$

Where S_{ij}=average sortie time in minutes for aircraft type i traveling to area of operation j

P=time to attach external lift in minutes

L=time to clear the sea-base in minutes

D_j=distance to area of operation j from the sea-base in nm

SL_i=speed of aircraft type i carrying an external load in knots

Z=time to approach the LZ in minutes

O=time to disengage the external lift in minutes

C=time to clear the LZ in minutes

SE_i=speed of aircraft type i traveling back to the sea-base without a load in knots

A=time to approach and land on the sea-base in minutes

R=time to re-fuel on the sea-base in minutes

By using the previously defined equation to develop sortie times and employing the "crew day" constraint, the following tables (one table for each sea-base location) give sortie duration and maximum number of sorties/day for each aircraft and each area of operation ashore.

Area of Operation	Distance to Sea-base (nm)	MV-22 sortie time (min)	Max # of sorties per MV-22 to area of operation	CH-53 sortie time (min)	Max # of sorties per CH-53 to area of operation
1	100	112	4	135	3
2	85	100	4	119	4
3	75	91	5	109	4
4	65	83	5	98	4
5	60	79	6	93	5
6	50	71	6	82	6
7	45	66	7	77	6
8	35	58	8	66	7

Table 11. Sea-base #1 Aircraft Sortie Information

Area of Operation	Distance to Sea-base (nm)	MV-22 sortie time (min)	Max # of sorties per MV-22 to area of operation	CH-53 sortie time (min)	Max # of sorties per CH-53 to area of operation
1	140	145	3	178	2
2	125	133	3	162	2
3	115	125	3	151	3
4	110	120	4	146	3
5	105	116	4	140	3
6	95	108	4	130	3
7	85	100	4	119	4
8	72	89	5	105	4

Table 12. Sea-base #2 Aircraft Sortie Information

Area of Operation	Distance to Sea-base (nm)	MV-22 sortie time (min)	Max # of sorties per MV-22 to area of operation	CH-53 sortie time (min)	Max # of sorties per CH-53 to area of operation
1	170	170	2	209	2
2	160	162	2	199	2
3	150	154	3	188	2
4	145	150	3	183	2
5	135	141	3	172	2
6	125	133	3	162	2
7	115	125	3	151	3
8	100	112	4	135	3

Table 13. Sea-base #3 Aircraft Sortie Information

This analysis uses lists of executable sorties for each available MV-22 to choose from when determining where each MV-22 travels a certain day. These lists are developed for each sea-base location and day of the operation and employ the "crew day" constraint and sortie time information previously discussed. For every day, each available MV-22 chooses exactly one list of sorties to perform. This ensures that the individual aircraft does not violate the daily "crew day" constraint and provides which areas ashore it delivers sustainment to. The following table provides an example of some lists of sorties, while aircraft are operating from sea-base #3 on day 2:

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Sortie List Number	# of Sorties to Area a1	# of Sorties to Area a7	# of Sorties to Area a8
1	2	1	0
2	2	0	1
3	1	0	0
4	1	0	2
5	1	0	1
6	1	2	0
7	1	1	0
8	1	1	1

Table 14. Example of Sortie Lists for an MV-22 to Execute in a Day while Operating from Sea-base #3

3. Aircraft Availability

Both aircraft attrition due to enemy interdiction and maintenance requirements cause a decrease in the number of aircraft available with the passage of time. Of the available aircraft, a certain number of them are dedicated to operational and other than normal sustainment missions (troop movement, MEDEVAC). The remaining non-dedicated aircraft determine the types and respective quantities of aircraft available for sustainment missions.

a) Enemy Interdiction of Aircraft

Enemy attrition of aircraft is analyzed at three different levels (high, medium, none). Each level has associated with it a percentage of initial in-theater aircraft attrited throughout the operation for both aircraft types. Table 14 shows the levels of attrition and their respective percentage and total number of aircraft attrited.

Level of Attrition	% of MV-22s Attrited	Total # of MV-22s Attrited	% of CH-53s Attrited	Total # of CH-53s Attrited
High	5	2.4	5	1.1
Medium	3	1.44	3	.66
None	0	0	0	0

Table 15. Aircraft Attrition due to Enemy Interdiction Over Entire Campaign

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After calculating total number of aircraft attrited for both MV-22 and CH-53E, determining on which day each attrition takes place is required. This is determined using the assumption that most aircraft attrition occurs at the beginning of the operation and that the enemy's anti-aircraft capability is continuously degraded by friendly forces as time increases. Mathematically this is determined with a linearly decreasing function representing percentage of total aircraft shot down occurring on day t (t = 1...14). Figure 4 illustrates this function, where:

$$\sum_{t=1}^{14} (\% \text{ of total aircraft attrited occuring on day } t) = 1.0$$
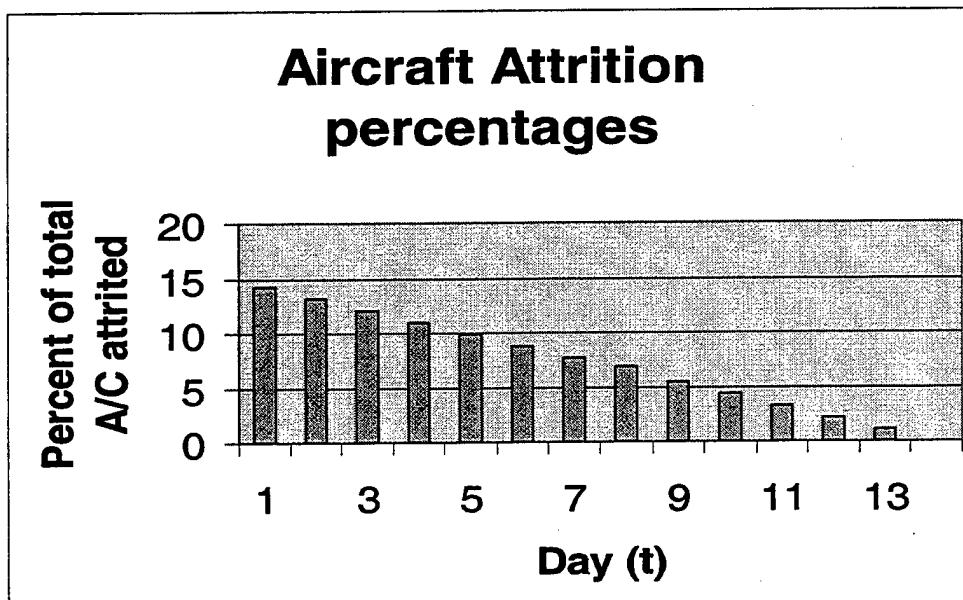

Figure 4. Percentage of Total Aircraft Shot Down Occurring on Day (t)

In this analysis, the cumulative number of aircraft attrited by the end of a day is calculated using the following equation:

$$A_{it} = \sum_{n=1}^{t} P_n * T_i$$

Where A_{it}=cumulative number of aircraft of type i attrited by the end of day t

P_n=percentage of total aircraft attrited on day n

T_i=total number of aircraft of type i attrited by the end of the operation

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b) Maintenance Readiness

It is assumed that initial aircraft readiness starts above projected readiness levels with cannibalization, priority for best equipment from CONUS and force closure time to work on maintenance. This analysis uses initial aircraft readiness rates of .90 for the MV-22 and .85 for the CH-53. It is also assumed that the aircrafts' readiness rates will decrease linearly to their projected sustained readiness rates. On day 7 of the 14-day operation the maintenance readiness of both aircraft are at their projected rates and remain at these rates through the end of the operation. This analysis uses projected maintenance readiness rates of .75 for the MV-22 and .70 for the CH-53 [Ref. 15]. In determining how many aircraft are available for operations on day t, the maintenance readiness rate on day t is applied to the number of aircraft available after enemy aircraft interdiction on day t-1 (for t = 2...14). Calculations resulting in non-integer values of aircraft available are rounded down for use in this analysis.

c) Aircraft in Support of Troop Movement Missions

In this scenario there is a requirement for the use of aircraft to support troop movement missions. The number of these missions is reduced, however, due to roughly 75% of the force ashore being classified as mobile. In determining how many aircraft to dedicate for troop movement missions, this analysis refers to similar studies conducted [Ref. 11]. In the referred study, the requirement was to move 1,000 troops each day, with an approximate 12,700 personnel ashore. This computes to a daily requirement to move 7.87% of the forces ashore with aircraft. In our scenario, 7.87% of approximately 4,300 troops ashore equates to a requirement to move 338 troops a day. This analysis assumes that there is a requirement to move each 1/3 of the total number of troops simultaneously. This translates into each 113 troops of the 338 total requiring to be moved at a single time during the day. With the MV-22 as the primary aircraft for troop movement and its capability to haul a maximum of 24 troops with one sortie, 5 MV-22s are dedicated each day for troop movement in this analysis and are not available for sustainment missions.

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d) *Aircraft Dedicated for MEDEVAC*

MEDEVAC missions normally require support from aircraft. This analysis uses some of the assumptions developed in [Ref. 15], with regard to dedicating aircraft to support medevacs. Part of these assumptions are that the landing force ashore does not generate a requirement greater than 49 troops per day to evacuate and that non-critical MEDEVAC will be done on the re-supply aircraft. The MV-22 can carry 12 litters and one is stationed ashore with the FARP. Another MV-22 is on standby at the sea-base. As the MV-22 ashore lifts off toward the sea-base with casualties, the other flies in to be on standby, ashore. The UH-1N, in fact, is used to support MEDEVAC missions in [Ref. 15]. However, due to the longer ship-to-shore distances and the Osprey's enhanced speed, the MV-22 is assigned to support these missions in this study.

e) *Tactical Bulk Fuel Distribution System (TBFDS)*

The final mission that aircraft are dedicated to, outside of the normal sustainment missions, is the delivery of fuel to the FARP with the TBFDS. The number of aircraft to dedicate to this mission is a function of the fuel required at the FARP, amount of fuel delivered per sortie, and the daily maximum number of daily sorties per CH-53. Both the computation of the fuel required at the FARP and the TBFDS fuel delivered per sortie (2,400 gallons) have been discussed. There is then a requirement to determine the daily maximum number of sorties per CH-53E, which is a function of average sortie time per day and the "crew day" constraint. Average sorties times are determined with the following equation:

$$S_i = L + (D_i * 60) / S + Z + F + C + (D_i * 60) / S + A + R$$

Where S_i=average sortie time in minutes for a CH-53 with TBFDS traveling to and from sea-base i

L=time to lift and clear the sea-base (2 minutes)

D_i=distance to the FARP from sea-base i (nm)

S=speed of CH-53 carrying the TBFDS (130 knots)

Z=time to approach the LZ (2 minutes)

F=time to unload fuel at the FARP (30 minutes)

C=time to clear the LZ in (2 minutes)

A=time to approach and land on the sea-base (2 minutes)

R=time to re-fuel on the sea-base (30 minutes)

By using the previously defined equation to develop sortie times and employing the "crew day" constraint, the following table displays sortie times and maximum number of sorties per aircraft:

Sea-base Number	Distance to the FARP from the sea-base (nm)	CH-53 w/TBFDS sortie time (min)	Max # of sorties per CH-53E w/TBFDS per day = S_i
1	45	110	4
2	85	146	3
3	115	174	2

Table 16. CH-53E with TBFDS Sortie Information

Using information provided in Table 16, the following equation determines the daily total number of CH-53s to dedicate to the mission of delivering fuel to the FARP:

$$C_i = \left\lceil \frac{F}{T * S_i} \right\rceil$$

Where C_i=total number of CH-53s to dedicate each day to the re-supply of fuel to the FARP with aircraft located at sea-base i

F=total daily fuel required at the FARP in gallons

T=total fuel moved with one CH-53E w/TBFDS sortie in gallons

S_i=maximum number of sorties per CH-53E w/TBFDS per day with aircraft located at sea-base i

This completes discussion of the methodology used and development of the data required.

V. PROBLEM FORMULATION

In this study's evaluation of SBL, the primary objective is to sustain forces ashore with deliveries of sustainment from available aircraft. This poses a challenge because everyday the number of aircraft available for sustainment missions is limited by aircraft maintenance readiness, enemy attrition of aircraft, and aircraft dedicated to other missions (e.g. troop movement, MEDEVAC, and TBFDS). When use of available aircraft sorties is not enough to deliver all sustainment required, then inventory of commodities held by units ashore should be utilized. If both the use of inventory ashore and deliveries of sustainment by aircraft are not enough to provide all sustainment required, then LCACs will have to be utilized to deliver the shortfall. If LCACs are used for transporting sustainment, then it should occur in such a manner that requires the least resources or effort needed to secure and/or defend the lines of communication ashore. This will be accomplished by minimizing both the number of daily LCAC sorties required and the distance from the single LCAC landing site to the area(s) ashore requiring LCAC delivery of sustainment. This desire to minimize both the number of daily LCAC sorties and the distance from the LCAC landing site to the area(s) ashore requiring sustainment from LCACs, motivates this study to use an optimization model.

The model keeps track of an individual aircraft's sorties, detailing what commodity is delivered to which area per sortie. Since aircraft fly integer values of sorties and not fractional values, Mixed Integer Programs (MIPs) are used to model this study's problem.

With deployment of forces on day 1 including some sustainment, problem modeling will focus on the resupply of forces ashore for days 2 through 14 of the operation only. MIPs possessing numerous integer variables, which are difficult to tightly bound, have associated with them memory size and run time problems. Resulting from this and in an attempt to minimize the number of integer variables, problem modeling is achieved through solving two separate MIPs in sequence, for each resupply day. Since it can be assumed that the number of CH-53s available for sustainment missions will always be much less than that of the MV-22s, the first program's objective is to employ the available CH-53s in support of minimizing the number of sorties required by MV-22s to

deliver sustainment ashore. The second program's objective function is to employ the available MV-22s in support of minimizing the number of LCAC sorties required to sustain the forces ashore and, in the event that LCAC sorties are required, to support the areas with the shortest distance to the LCAC landing site. If the resulting number of LCAC sorties is zero, aircraft can deliver all sustainment to forces ashore in the case study. The model considers the operation one day at a time and in doing so minimizes daily LCAC sorties for days 2-14 of the operation.

As a result of the model being comprised of two separate programs that are executed for each day of the operation and one day at a time, there is a requirement to transfer information between both programs and days. The information that requires transfer between days is the end of day inventory of commodities on day t, whose value will be passed on to represent the beginning of day inventory of commodities on day $t+1$. The information that requires transfer between programs is the amount of commodity requiring MV-22 delivery, after CH-53 deliveries have taken place.

A problem that arises from solving the two models one day at a time is the possibility of forces ashore consuming inventory of commodity too early in the operation. If inventory is consumed on a day where available aircraft can deliver all required sustainment, then later in the operation, when there are fewer available aircraft, there will be less inventory to help minimize the number of LCAC sorties required. In this example, the overall problem modeling did not achieve the optimal objective values for daily LCAC sorties. Resulting from this problem, a secondary objective function is used in the MV-22 program, attempting to maximize the inventory of commodities carried by logistics vehicles ashore at the end of the day. This function's purpose is to drive the model to use all available aircraft sorties to deliver sustainment prior to using commodities carried by any logistics vehicles. This is desired since the number of available sorties on day t will be equal to or greater than the number of available sorties on day $t+1$ due to aircraft attrition and maintenance readiness. Therefore, the ability to deliver sustainment with aircraft becomes increasingly difficult with each day the operation progresses. Resulting from this, consumption of inventory (commodities) shouldn't take place till later in the operation when most needed. The maximum amount of inventory that will be held in a

given day is bounded above by the capacity of the logistics vehicles present. The secondary objective function's maximum effect upon the model's overall objective function will be very small relative to the primary objective function's effect.

The major drawback with this study's model is that it uses a myopic vice a multi-period approach. This approach was chosen after numerous run time and branch and bound memory problems encountered by attempting to model the problem with multi-period MIPs. Resulting from the model's myopic approach is the fact that LCAC sorties are not minimized for the entire operation, for case studies where there is inventory ashore. A multi-period model would be able to look over the entire duration of the operation and observe when the best time would be to consume inventory in support of minimizing LCAC sorties. This study's model instead minimizes LCAC sorties one day at a time but also attempts to maintain as much inventory as possible at the end of the day, in support of the next day's sustainment effort. As a result, this study's model attempts to maximize delay of the day when the first LCAC sortie is required.

A. INDICES

a areas of operation ashore, (a1...a8)

chc CH-53 and its crew available for sustainment missions, (ex. chc1...chc12) [To date, Marine aviation operates with equal number of aircraft and crews.]

com a list of sorties for an MV-22 to execute in a day, (ex. com1...com68)

k commodity, (k1=water, k2=fuel, k3=rations, k4=ammo)

mvc MV-22 and its crew available for sustainment missions, (ex. mvc1 ... mvc43)

p type of aircraft, (MV22, CH53)

s category of commodity delivered by LCAC, (water, fuel, dry)

t day, (t1...t14)

B. INDEX SETS

$A_t \in a$ areas of operation where forces are located on day t

$K \in k$ the commodities that area $a1$ has the ability to maintain an inventory of

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C. PARAMETERS

$alpha1_a$ Artificial penalty value associated with a required MV-22 equivalent sortie in support of area a that does not get executed by CH-53s (unit less)

$alpha2_a$ Artificial penalty value associated with one LCAC sortie delivering sustainment to support area a (unit less)

$beginv_{k,a,t}$ The inventory quantity of commodity k located at area of operation a at the beginning of day t (lbs or gal)

$cap_{k,a}$ The logistics vehicles capacity to hold commodity k in area a (lbs or gal)

$cons1_{k,a,t}$ Qty of commodity k consumed in area of operation a on day t (lbs or gal)

$cons2_{k,a,t}$ The quantity of commodity k consumed at area a not supported by CH-53 deliveries on day t (lbs or gal)

$comwt_{t+1}$ The total number of MV-22 sorties required to deliver water, fuel and ammunition to area $a1$ on day $t+1$

$crewt$ Max time that a transporter crew can operate per day, "crew time" (min)

$mxld_{k,p,a}$ Maximum qty of commodity k that can be lifted by aircraft type p to area of operation a with one sortie(lbs or gal)

$mxldlc_s$ The maximum quantity of commodity type s that can be transported by one LCAC sortie (lbs or gal)

$mveqsort_{k,a}$ The number of MV-22 equivalent sorties that a CH-53 sortie can provide when delivering commodity k to area a

$mvstrqd_{k,a,t}$ The number of MV-22 sorties required to support the consumption of commodity k at area a on day t

$mvstrqd1_{k,a,t}$ The number of MV-22 sorties required to support the quantity of the consumption of commodity k at area a on day t minus the commodity inventory

$\text{mvstrqd2}_{k,a,t}$ The number of MV-22 sorties (integer) required to support the consumption of commodity k at area a on day t, after CH-53 deliveries of sustainment take place

$\text{mvstrqd3}_{a,t}$ The total number of MV-22 sorties (integer) required to support the consumption of all commodities at area a on day t, after CH-53 deliveries of sustainment take place

$\text{numsort}_{a,com}$ The number of sorties to area a that a single MV-22 can execute when scheduled to fly the list of sorties *com*

$\text{st}_{p,a}$ Average sortie time for transporter p to conduct a sustainment mission to area of operation a (min)

D.   VARIABLES

$\text{CH}_{chc,k,a,t}$ (Integer) # of sorties flown by CH-53 crew *chc* carrying only commodity k to objective area a on day t

$\text{CHDLR}_{k,a,t}$ (Positive) Amount of commodity k delivered to area a by CH-53s on day t (lbs or gal)

$\text{CSHT}_{k,a,t}$ (Positive) Amount of commodity k shortfall in area a on day t(lbs or gal)

$\text{D}_{mvc,com,t}$ (Binary) An indicator that is 1 if MV-22 crew *mvc* performs the list of sorties *com* on day t and 0 otherwise

$\text{INV}_{k,a,t}$ (Positive) Amount of commodity k unconsumed in area of operation a at the end of day t (lbs or gal)

$\text{LCAC}_{s,a,t}$ (Integer) # of sorties flown by LCACs carrying commodity s in support of area a on day t

$\text{MVEQV}_{k,a,t}$ (Positive) Number of MV-22 equivalent sorties carrying commodity k to area a executed by CH-53s on day t

$\text{MVDLR}_{k,a,t}$ (Positive) Amount of commodity k delivered to area a by MV-22s on day t (lbs or gal)

$\text{MVSHT}_{a,t}$ (Positive) Total number of MV-22 sorties to area a that are **not** accomplished by the end day t

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$\text{REMAIN}_{k,a,t}$ (Free) Amount of commodity k requiring MV-22 delivery to area a on day t after CH-53 deliveries have taken place (lbs or gal); If the value is negative then CH-53 deliveries satisfy the total requirement and/or an inventory can be held resulting from a surplus of delivery.

$\text{SHT}_{a,k,t}$ (Positive) # of MV-22 sorties to area a carrying commodity k that are **not** executed by the end of day t

E. MATHEMATICAL FORMULATION

1. CH-53 Sustainment Model

$$Min \sum_{k} \sum_{A_t \varepsilon \, a} alpha1_a * \left(mvstrqd1_{k,a,t} - MVEQV_{k,a,t} \right)$$

Subject to:

$$\sum_{k} \sum_{A_t \varepsilon \, a} CH_{chc,k,a,t} * st_{"CH53",a} \leq crewt \qquad \forall chc \qquad (1)$$

$$\sum_{chc} CH_{chc,k,a,t} * mveqsort_{k,a} \geq MVEQV_{k,a,t} \qquad \forall A_t \in a,k \qquad (2)$$

$$MVEQV_{k,a,t} \leq mvstrqd1_{k,a,t} \qquad \forall A_t \in a,k \qquad (3)$$

$$\sum_{chc} CH_{chc,k,a,t} * mxld_{k,"CH53",a} = CHDLR_{k,a,t} \qquad \forall A_t \in a,k \qquad (4)$$

$$cons1_{k,a,t} - CHDLR_{k,a,t} = REMAIN_{k,a,t} \qquad \forall A_t \in a,k \qquad (5)$$

$$0 \leq CH_{chc,k,a,t} \leq \left\lfloor \frac{crewt}{st_{"CH53",a}} \right\rfloor \qquad \forall chc,k,a,t \qquad (6)$$

$$MVEQV_{k,a,t}, CHDLR_{k,a,t} \geq 0 \qquad \forall k,a,t \qquad (7)$$

$$CH_{chc,k,a,t} \in Integer \qquad \forall chc,k,a,t \qquad (8)$$

The objective function minimizes the number of sorties required by MV-22s to deliver sustainment ashore. A penalty value for each area attempts to allow sorties for different areas to be additive. The penalty's goal is to penalize "sorties required by MV-22s" more if they are associated with areas that an MV-22 can fly fewer sorties to per

day. The penalty value assigned to area a is a function of the maximum number of daily sorties executed by an MV-22. The following equation demonstrates this relationship:

$$alpha1_a = \left. \left| \frac{crewt}{st_{"MV22","a8"}} \right| \middle/ \left| \frac{crewt}{st_{"MV22",a}} \right| \right.$$

The "crew day" constraint, equation (1), ensures that CH-53s do not exceed their maximum operational time. The number of MV-22 equivalent sorties executed by CH-53s carrying commodity k to area a is figured in equation (2). Equation (3) ensures that CH-53s do not fly more MV-22 equivalent sorties than required. The amount of commodity k delivered to area a by CH-53s is figured in equation (4). The amount of commodity k requiring MV-22 delivery to area a after CH-53 deliveries have taken place is determined in equation (5). Equation (6) places an upper bound on the integer variable of CH-53 sorties. Equations (7) and (8) further define the bounds of the model's variables.

2. MV-22 Sustainment Model

For days 2 through 13 the objective function follows:

$$Min \quad \sum_{s} \sum_{A,\varepsilon a} alpha2_a * LCAC_{s,a,t} - \sum_{K \varepsilon k} \left(\frac{INV_{k,"a1",t}}{cap_{k,"a1"}} \right) * \left(\frac{mvstrqd_{k,"a1",t+1}}{comwt_{t+1}} \right)$$

For day 14 (the last day of the operation) the objective function is as follows:

$$Min \quad \sum_{s} \sum_{A_{t14}\varepsilon a} alpha2_a * LCAC_{s,a,t14}$$

Subject to:

$$\sum_{com} D_{mvc,com,t} = 1 \qquad\qquad \forall mvc \qquad (1)$$

$$\sum_{mvc} \sum_{com} numsort_{com,a} * D_{mvc,com,t} = mvstrqd3_{a,t} - MVSHT_{a,t} \quad \forall A_t \in a \qquad (2)$$

$$\sum_{k} SHT_{k,a,t} = MVSHT_{a,t} \qquad\qquad \forall A_t \in a \qquad (3)$$

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MV-22 Sustainment Model (Continued)

$$MVDLR_{k,a,t} \le \left(mvstrqd2_{k,a,t} - SHT_{k,a,t}\right) * mxld_{k,"MV22",a} \quad \forall A_t \in a,k \qquad (4)$$

$$INV_{k,a,t} - CSHT_{k,a,t} = beginv_{k,a,t} + MVDLR_{k,a,t} - cons2_{k,a,t} \quad \forall A_t \in a,k \qquad (5)$$

$$CSHT_{"k1",a,t} \le LCAC_{"water",a,t} * mxldlc_{"water"} \qquad \qquad \forall A_t \in a \qquad (6)$$

$$CSHT_{"k2",a,t} \le LCAC_{"fuel",a,t} * mxldlc_{"fuel"} \qquad \qquad \forall A_t \in a \qquad (7)$$

$$CSHT_{"k3",a,t} + CSHT_{"k4",a,t} \le LCAC_{"dry",a,t} * mxldlc_{"dry"} \qquad \forall A_t \in a \qquad (8)$$

$$0 \le INV_{k,a,t} \le cap_{k,a} \qquad \qquad \forall k,a,t \qquad (9)$$

$$0 \le LCAC_{"water",a,t} \le \left\lceil cons2_{"k1",a,t} \middle/ mxldlc_{"water"} \right\rceil \qquad \forall a,t \qquad (10)$$

$$0 \le LCAC_{"fuel",a,t} \le \left\lceil cons2_{"k2",a,t} \middle/ mxldlc_{"fuel"} \right\rceil \qquad \forall a,t \qquad (11)$$

$$0 \le LCAC_{"dry",a,t} \le \left\lceil cons2_{"k3",a,t} + cons2_{"k4",a,t} \middle/ mxldlc_{"dry"} \right\rceil \qquad \forall a,t \qquad (12)$$

$$CSHT_{k,a,t}, MVDLR_{k,a,t}, MVSHT_{a,t}, SHT_{k,a,t} \ge 0 \qquad \forall k,a,t \qquad (13)$$

$$SHT_{k,a,t}, LCAC_{s,a,t} \in Integer \qquad \qquad \forall k,a,t,s \qquad (14)$$

$$D_{mvc,com,t} \in (0,1) \qquad \qquad \forall mvc,com,t \qquad (15)$$

The objective function for day 14 minimizes the number of LCAC sorties required to sustain the forces ashore. The weighing of the LCAC sorties based upon the area supported is to ensure that the priority of LCAC sorties goes to the most southern areas of operation (shorter lines of communication to secure). The objective function for days 2 – 13 contains the same objective function as day 14, however, also contains a secondary objective function. This secondary objective function attempts to maximize all commodity inventory levels at the end of the day in area *a1*. The minimum value that this function can obtain is –1. The individual commodities (*k = k1, k2,* and *k4*) are weighted in this function by the total number of MV-22 sorties required to deliver commodities to area *a1* the following day. The weight of commodity *k* is determined by the total number of MV-22 sorties required to deliver commodity *k* to area *a1*, the following day, divided by

the total number of MV-22 sorties to required to deliver all commodities *k1*, *k2*, and *k4* to area *a*.

Equation (1) ensures that each MV-22 available for sustainment missions is scheduled to execute one list of sorties. The total number of MV-22 sorties to area *a* that are not accomplished by the end of the day is figured in equation (2). The total number of MV-22 sorties to area *a* carrying commodity *k* that are not executed by the end of the day is figured in equation (3). The amount of commodity *k* delivered to area *a* by MV-22s is determined in equation (4). The inventory constraint is defined in equation (5). Inventory left at the end of the day is a function of the previous day's inventory and present day's commodity consumption and commodity delivered by aircraft. If commodity demand is not met by prior day's inventory and present day's deliveries, then a shortfall variable will assume a positive value. Equations (6), (7), and (8) ensure that commodity shortfalls are supported by LCAC sorties delivering sustainment. The commodity inventory is bounded above by the capacities of logistics vehicles in equation (9). Equations (10), (11), and (12) place an upper bound on the integer variable of the number of LCAC sorties. Equations (13), (14), and (15) further define bounds on the model's variables.

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VI. RESULTS

This study uses three variables (levels of aircraft attrition due to enemy interdiction, ship-to-objective distances, and deployment of logistics vehicles carrying commodities) to develop 27 different case studies. The levels of aircraft attrition are classified as high, medium, and none. The levels of ship-to-objective distances are classified as long, medium and short. Finally, the levels of logistics vehicles deployed are classified as a heavy footprint, a light footprint, and no deployment.

This study then models the number of aircraft and LCAC sorties per day required to deliver sustainment ashore for each day of the operation. The model's objective function both minimizes the number of LCAC sorties required and, in the event that LCAC sorties are required, attempts to use these sorties to deliver sustainment to areas that are located the shortest distance from the LCAC landing site (location of landing site is in the southern part of the AOR). Important information that the results of the model provide include:

- The total number of LCAC sorties required for the entire operation

- The day on which LCAC sorties are first required

- The maximum number of daily LCAC sorties

- The areas ashore that require support from LCAC sorties

An increase in the level of aircraft attrition reduces the number of available aircraft and makes it increasingly more difficult for aircraft to deliver all required sustainment. An increase in the ship-to-objective distances decreases both the total number of aircraft daily sorties performed by aircraft and an aircraft's maximum weight lifted per sortie. Therefore, increasing ship-to-objective distances makes it increasingly more difficult for aircraft to deliver all required sustainment, as well, but also helps protect amphibs from a high level enemy threat. An increase in the footprint of logistics vehicles and the commodities they carry initially decreases the amount of sustainment required for delivery by ship-to-shore transporters but also increases the footprint of the forces ashore, thus

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increasing the daily consumption of commodities, possibly slowing down momentum, and requiring additional resources dedicated to the security of these vehicles.

This chapter provides model results as well as a discussion of the insight yielded by these results. Results should reflect that both an increase in aircraft attrition due to enemy interdiction and ship-to-objective distances will increase the total number of LCAC sorties required for the entire operation. An increase in the footprint of logistics vehicles should result in both a delay of the day on which LCAC sorties are first required and a decrease in the total number of LCAC sorties required for the entire operation.

Modeling is implemented in the General Algebraic Modeling System (GAMS) [Ref. 21] with the CPLEX solver [Ref. 22]. The size of both the CH-53 Sustainment Model and the MV-22 Sustainment Model (see pages 42 and 43 respectfully) depend upon the number of aircraft or crews available for sustainment missions. With 7 CH-53s available for sustainment missions, the CH-53 Sustainment Model has approximately 88 equations and 289 variables, of which 112 are discrete. With 34 MV-22s available for sustainment missions, the MV-22 Sustainment Model has approximately 88 equations and 2,791 variables, of which 1,368 are discrete.

The time required to solve each model also depends upon the number of aircraft or crews available as well as the relative integer termination tolerance; this is the difference between the best integer solution and the best known lower bound, divided by the absolute value of the best integer solution. With a relative tolerance of .0001 and having 10 CH-53s available for sustainment missions, the time to solve the CH-53 Sustainment Model is approximately 10 minutes. However, having only 5 CH-53s available and maintaining a relative tolerance of .0001, the time to solve the CH-53 Sustainment Model is approximately 1 minute. With a relative tolerance of .000001, the time to solve the MV-22 Sustainment Model is approximately 1 minute. Model runs for this study used a personal computer equipped with a Pentium II 333 MHZ processor and 296 MB of RAM.

A. 27 CASE STUDIES

Tables 17-19 reflect the total number of LCAC sorties required over 14 days to sustain forces ashore in all 27 case studies.

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Level of Aircraft Attrition due to Enemy Interdiction	Long Distance, Sea-base #3 to Shore Distance (170-100 nm)	Medium Distance, Sea-base #2 to Shore Distance (140-72 nm)	Short Distance, Sea-base #1 to Shore Distance (100-35nm)
High (5%)	78 LCAC sorties	0 LCAC sorties	0 LCAC sorties
Medium (3%)	71 LCAC sorties	0 LCAC sorties	0 LCAC sorties
None (0%)	46 LCAC sorties	0 LCAC sorties	0 LCAC sorties

Table 17. No Deployment of Logistics Vehicles

Level of Aircraft Attrition due to Enemy Interdiction	Long Distance, Sea-base #3 to Shore Distance (170-100 nm)	Medium Distance, Sea-base #2 to Shore Distance (140-72 nm)	Short Distance, Sea-base #1 to Shore Distance (100-35nm)
High (5%)	50 LCAC sorties	0 LCAC sorties	0 LCAC sorties
Medium (3%)	43 LCAC sorties	0 LCAC sorties	0 LCAC sorties
None (0%)	26 LCAC sorties	0 LCAC sorties	0 LCAC sorties

Table 18. Light footprint of Logistics Vehicles supporting the Northern Forces

Level of Aircraft Attrition due to Enemy Interdiction	Long Distance, Sea-base #3 to Shore Distance (170-100 nm)	Medium Distance, Sea-base #2 to Shore Distance (140-72 nm)	Short Distance, Sea-base #1 to Shore Distance (100-35nm)
High (5%)	50 LCAC sorties	0 LCAC sorties	0 LCAC sorties
Medium (3%)	43 LCAC sorties	0 LCAC sorties	0 LCAC sorties
None (0%)	18 LCAC sorties	0 LCAC sorties	0 LCAC sorties

Table 19. Heavy footprint of Logistics Vehicles supporting the Northern Forces

With the exception of operating from Sea-base #3, delivery of sustainment to the forces ashore can be accomplished without the use of LCACs and accounts for aircraft unavailable due to their assignment to perform tactical missions (e.g. troop movement and MEDEVAC). This result, as will be seen, holds for much higher aircraft attrition rates as well. This information should give planners, involved with the subject scenario, encouraging insight into the capability of sea-base transport aircraft to support SBL, where there is a medium to low enemy threat to the amphibs (i.e. when the sea-base is relatively close to the areas of operation ashore).

Since only the ship-to-objective distances provided by Sea-base #3 imply a requirement for LCAC sorties, this case is examined in more detail. In addition to the total number of LCAC sorties required for the entire operation, the distribution of these

sorties over the days of the operation is examined and the day on which these LCAC sorties are first required is of primary interest.

B.   SEA-BASE #3 CASE STUDIES

Table 20 details the total number of LCAC sustainment sorties required for the entire operation when operating from Sea-base #3. In these case studies, LCAC sorties are operated to a single beach landing site located in the southern part of the AOR, where logistics vehicles carrying the commodities required, drive off the LCAC(s) and travel a minimum of 10 nm to area of operation 8 or a maximum of 90 nm north to area of operation 1. The formulation of the model attempts to deliver all sustainment with only aircraft but when this attempt is not feasible, the model then minimizes the number of LCAC sorties required to support the northern areas (e.g. area of operation 1). Information provided in the following tables should help planners, involved with the scenario, when the amphibs are subject to a high enemy threat and therefore the sea-base must be located far from the areas of operation ashore.

Level of Aircraft Attrition due to Enemy Interdiction	Heavy footprint (2 DOS ISO area 1) of Logistics Vehicles	Light footprint (1 DOS ISO area 1) of Logistics Vehicles	No Deployment of Logistics Vehicles
High (5%)	50 LCAC sorties	50 LCAC sorties	78 LCAC sorties
Medium (3%)	43 LCAC sorties	43 LCAC sorties	71 LCAC sorties
None (0%)	18 LCAC sorties	26 LCAC sorties	46 LCAC sorties

Table 20. Far Ship to Shore Distance (Sea-base #3)

The decision to deploy logistics vehicles ashore reduces the number of LCAC sorties required to deliver sustainment by 20 or more when compared to the decision not to deploy logistics vehicles. When comparing a light footprint of logistics vehicles to a heavy footprint of logistics vehicles, a heavy footprint does not reduce the total number of LCACs sorties required when there is a medium or high level of aircraft attrited. This can be explained by the presence of more vehicles and people that require more commodity sustainment and therefore more aircraft sorties to support. When there is no attrition of aircraft, the decision to deploy a heavy footprint of logistics vehicles ashore reduces the number of LCAC sorties required by 8 when compared to the decision to deploy a light

footprint. This is different than the case where there is aircraft attrition because both the number of aircraft available and commodity carried by these vehicles help push back the day on which LCAC sorties are first required to later in the operation. Based on just this information planners might decide to deploy a light footprint of logistics vehicles vice a heavy footprint. Before making this decision, however, planners need to observe more detailed information concerning the case studies involving Sea-base #3.

Figures 5-7 reflect the total number of LCAC sorties required to deliver sustainment per day for each of the 9 case studies involving Sea-base #3.
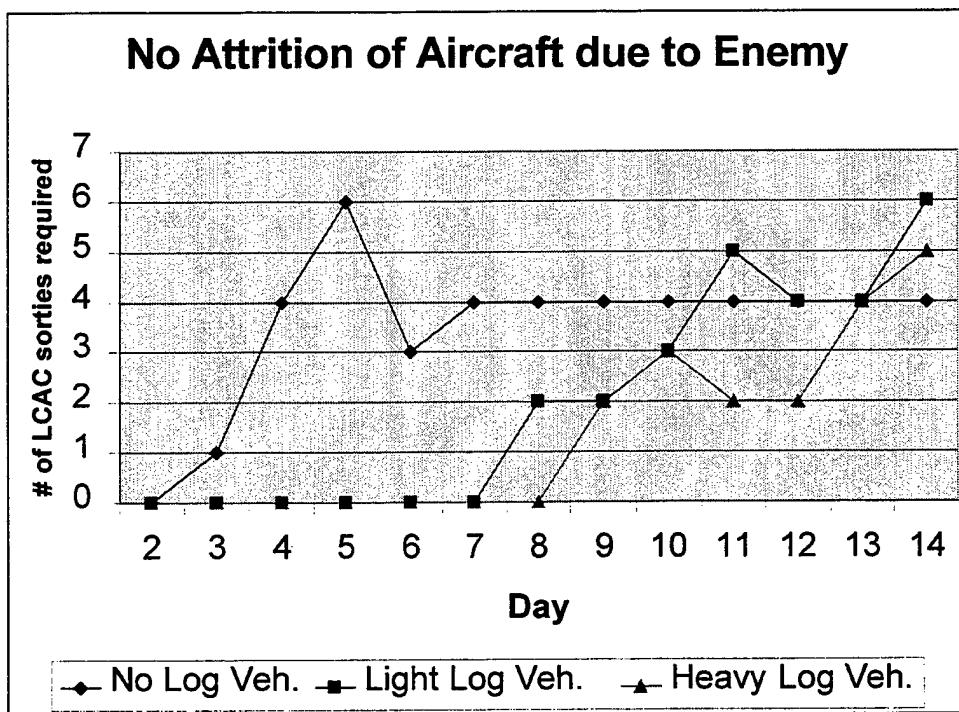

Figure 5. Sea-Base #3, LCAC Sorties Required per Day of the Operation
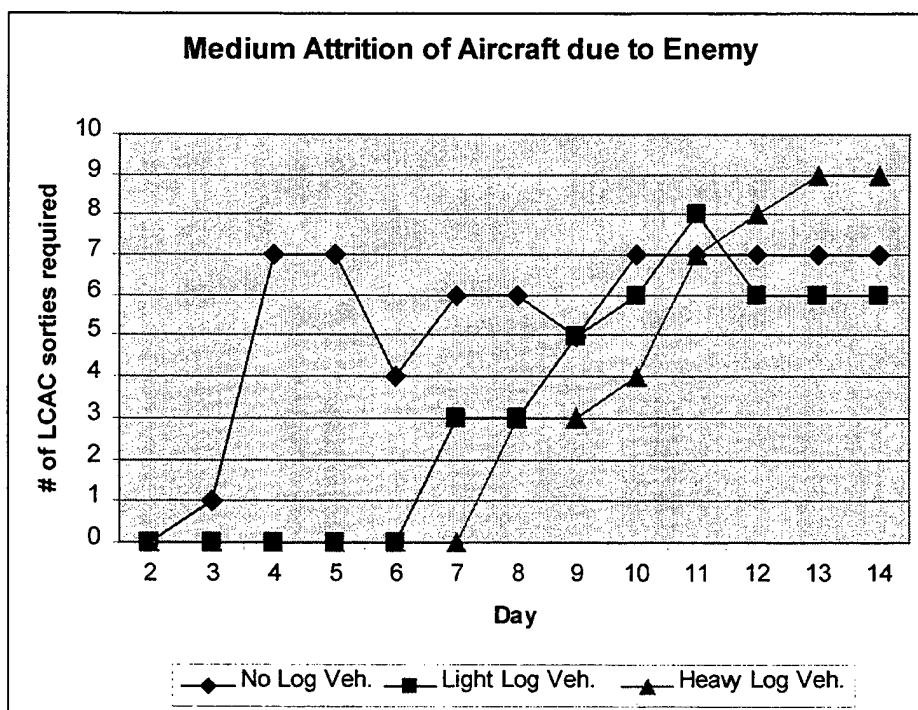
*Figure 6. Sea-base #3, LCAC Sorties Required per Day of the Operation*
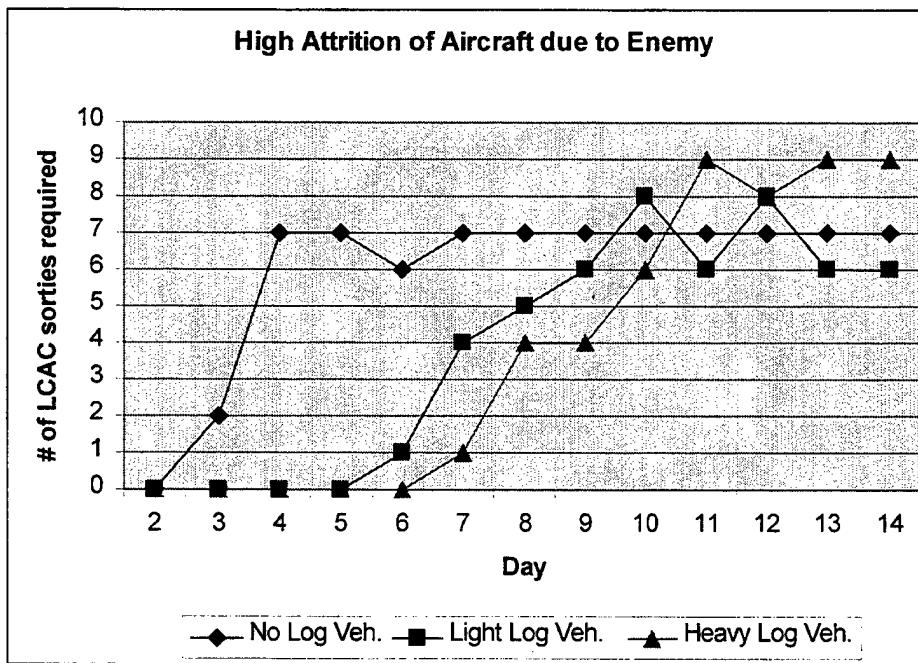
Figure 7. Sea-base #3, LCAC Sorties Required per Day of the Operation

Results in Figure 5 show that when there is no attrition of aircraft, the day on which LCAC sorties are first required is day 3, 8, and 9 for the case studies where no logistics vehicles are deployed, a light logistics vehicle footprint is deployed and a heavy logistics vehicle footprint is deployed, respectively. This is important information, since both the security of LCACs and the security of lines of communication ashore could possibly improve as the number of days into the operation increases. This information provides more support for the argument to deploy logistics vehicles ashore. An additional argument for the deployment of logistics vehicles would be that planners should feel more comfortable delivering sustainment ashore with 6 LCAC sorties on day 14 than delivering sustainment ashore with 6 LCAC sorties on day 5. This example provides the different days on which the maximum number of daily LCAC sorties is executed for the case studies involving a light footprint of logistics vehicles and no deployment of logistics vehicles, respectively.

Observing Figures 6 and 7 shows that between each level of attrition, there is a one-day reduction of the day on which LCAC sorties are first required, for both footprints of logistics vehicles. Of the total number of LCAC sorties required per day (information contained in Figures 5-7), a certain number might possibly be required to support northern areas of operation ashore. This information is important to know since it would be more desirable to have logistics vehicles, coming off LCACs, to not travel a long distance ashore. By having logistics vehicles, coming off LCACs, support mostly the southern areas, the lines of communication ashore are much shorter. Thus, in this case it is much easier to secure the vehicles' movement ashore.

Figures 8-10 reflect the number of LCAC sorties per day required to deliver sustainment in support of the northern areas ashore (e.g. area of operation 1 and 2).
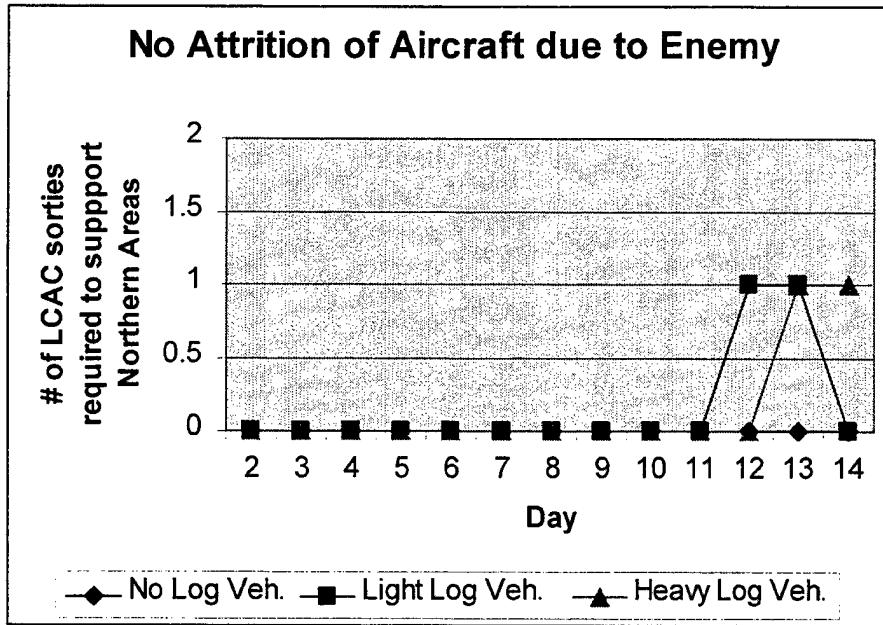
*Figure 8. Sea-base #3, LCAC Sorties Required per Day to Support Northern Areas*
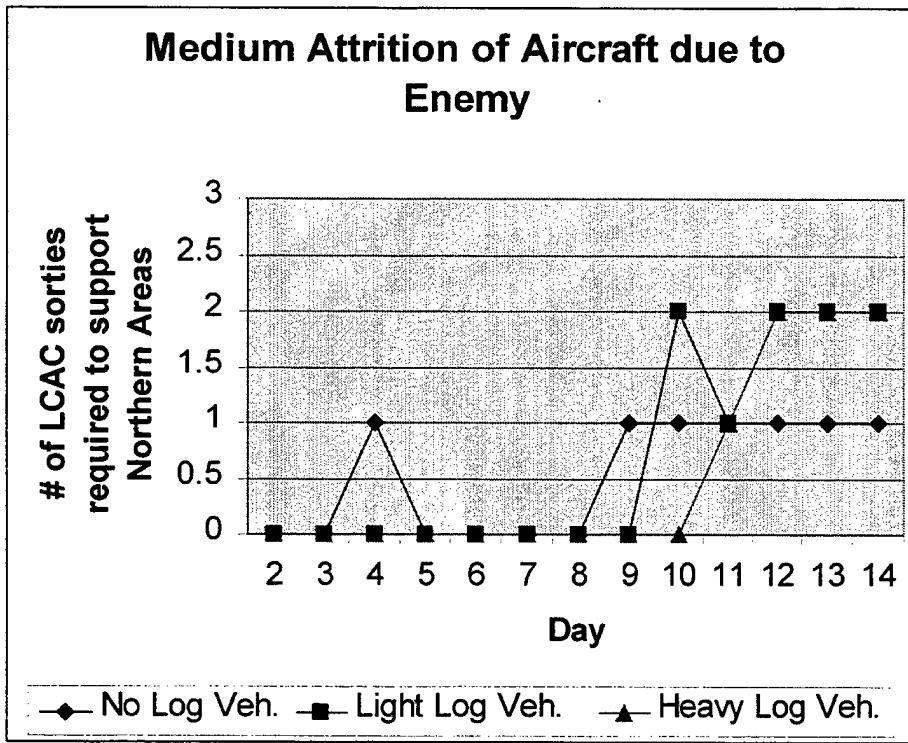
Figure 9. Sea-base #3, LCAC Sorties Required per Day to Support Northern Areas
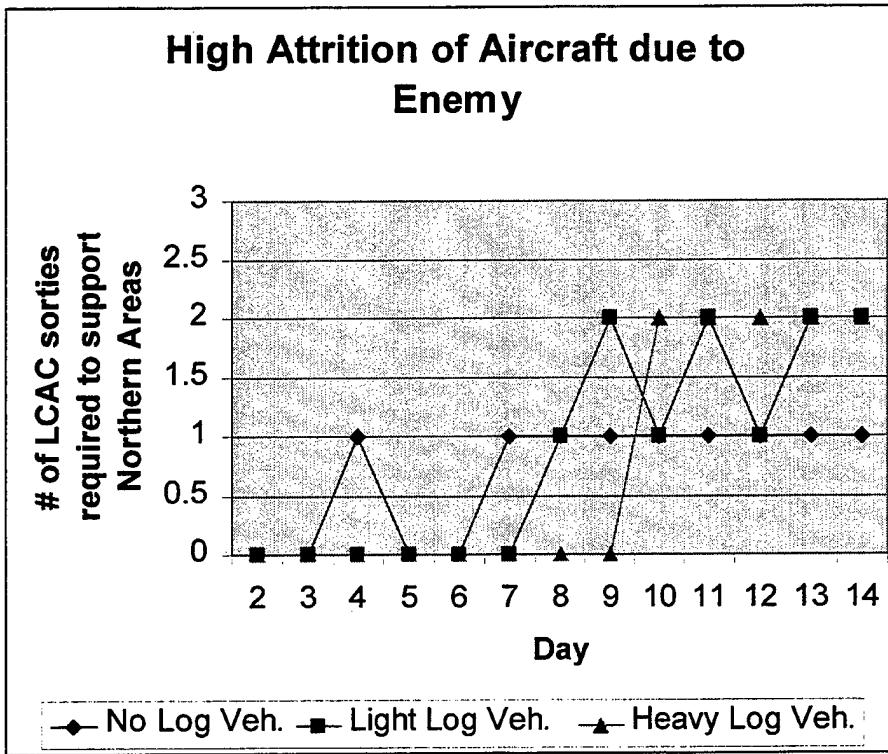
Figure 10. Sea-base #3, LCAC Sorties Required per Day to Support Northern Areas

Observing Figure 8, it is interesting to note that in the event of no aircraft attrition and no deployment of logistics vehicles, there is no requirement for LCACs to support the northern areas. This is explained by the increased consumption of commodities when deploying additional forces ashore, which translates into an increased number of aircraft sorties required. Also interesting to note is the day on which the LCAC sorties are first required to support the northern areas is day 12 and day 13 for a light footprint and a heavy footprint of logistics vehicles, respectively.

Figures 9 and 10 show that with aircraft attrition and no logistics vehicles deployed, LCAC sorties in support of the northern areas will start on day 4 of the operation. This should be of interest to planners because in this scenario, it is very likely that the road(s) from the LCAC landing site to the northern areas may not be secured by day 4 of the operation. With the deployment of logistics vehicles, however, if there is attrition of aircraft, the day on which LCAC sorties are first required to deliver sustainment in support of the northern areas wouldn't take place till some day between and including days 8-11 of the operation.

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C.   EXCURSION

In an attempt to gain better insight into the model's sensitivity to changes in aircraft attrition, an excursion was analyzed using two to three times as much attrition. Even by increasing the percentage of aircraft attrited to 15%, delivery of sustainment can be accomplished without the use of LCAC when operating from either Sea-base #1 or #2 locations. Table 21 reflects the total LCAC sorties required for sustainment delivery for these case studies with higher levels of aircraft attrition when operating from Sea-base #3.

Percentage of Total Aircraft Attrited during Operation	Heavy footprint (2 DOS ISO area 1) of Logistics Vehicles	Light footprint (2 DOS ISO area 1) of Logistics Vehicles	No Deployment of Logistics Vehicles
15%	93 LCAC sorties	97 LCAC sorties	110 LCAC sorties
10%	76 LCAC sorties	79 LCAC sorties	102 LCAC sorties
5%	50 LCAC sorties	50 LCAC sorties	78 LCAC sorties

Table 21. Far Ship to Objective Distance (Sea-base #3)

With an increase in the level of aircraft attrition, the difference in the number of LCAC sorties required gets increasingly smaller when comparing the decision to deploy logistics vehicles or not. This occurs due to the inventory of the logistics vehicles being consumed earlier on in the operation, caused by not having enough aircraft to deliver all required supplies, and due to the logistics vehicles adding to the daily sustainment requirements. Even with increasing the percentage of aircraft attrited, the difference of total LCAC sorties required between the two footprints of logistics vehicles is very small and as a result a preference might be to decide on deploying a light footprint of logistics vehicles vice a heavy footprint.

Figures 11 and 12 reflect total number of LCAC sorties required per day with 10% and 15% attrition of aircraft. Observing these results shows that increasing aircraft attrition results in a decrease in the difference of the day on which LCAC sorties are first required when comparing decisions to deploy logistics vehicles to the decision not to deploy logistics vehicles. The day on which LCAC sorties are first required, when no

logistics vehicles are deployed, is on day 3 (the same day for the case study involving no aircraft attrition). When logistics vehicles are deployed, however, this day is between days 5-7 of the operation (as opposed to days 8-9 for the case studies involving no aircraft attrition). Observing these results also shows that by deploying a heavy logistics vehicle footprint instead of a light footprint, 1-2 more additional days will be gained before the occurrence of the day on which LCAC sorties are first required. This information should help planners in situations where a decision needs to be made concerning the amount of logistics vehicles to deploy ashore.


10% Aircraft Attrition due to Enemy
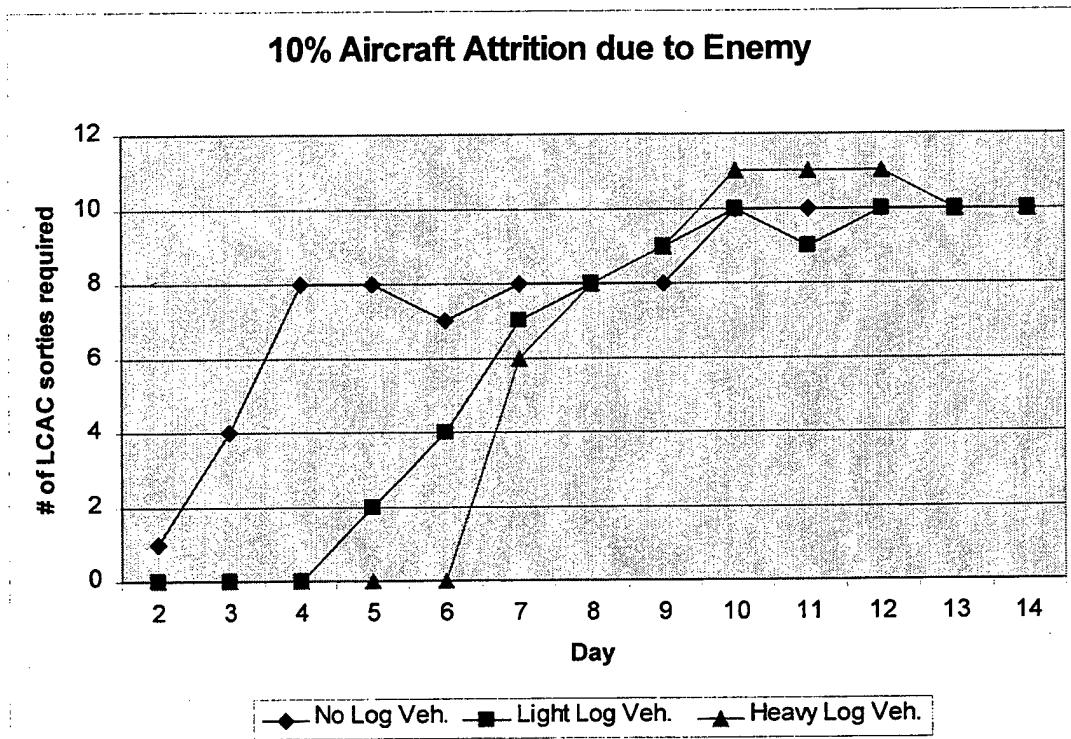
Figure 11. Sea-base #3, LCAC Sorties Required per Day

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15% Aircraft Attrition due to Enemy
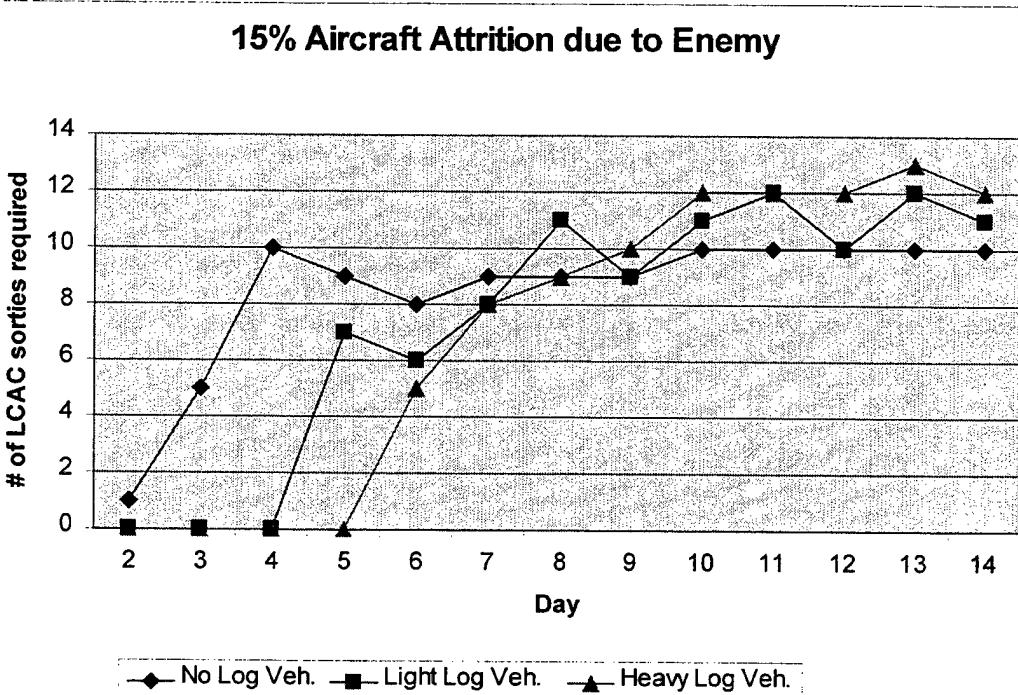
Figure 12. Sea-base #3, LCAC Sorties Required per Day

Figures 13 and 14 reflect the number of LCAC sorties per day required to support the northern areas with 10% and 15% aircraft attrition. Observing these results shows that increasing aircraft attrition also decreases the day on which LCAC sorties are first required to support the northern areas, when comparing deploying logistics vehicles to not deploying logistics vehicles. The day on which LCAC sorties in support of the northern areas are first required is on day 4 and when logistics vehicles are deployed is someday between days 7-9 or on day 5. Observing these results also shows that by deploying a heavy logistics vehicle footprint vice a light footprint 2-3 more additional days will be gained before the occurrence of the day on which LCAC sorties are first required to support the northern areas. This information could possibly influence decision makers to choose deploying a heavy footprint over a light one.

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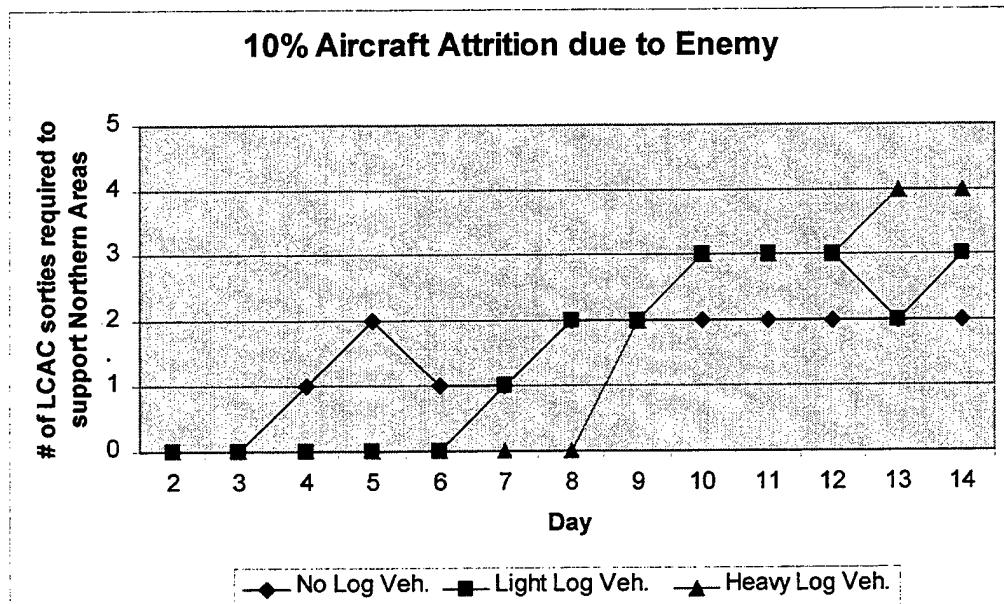
Figure 13. Sea-base #3, LCAC Sorties Required per Day to Support the Northern Areas
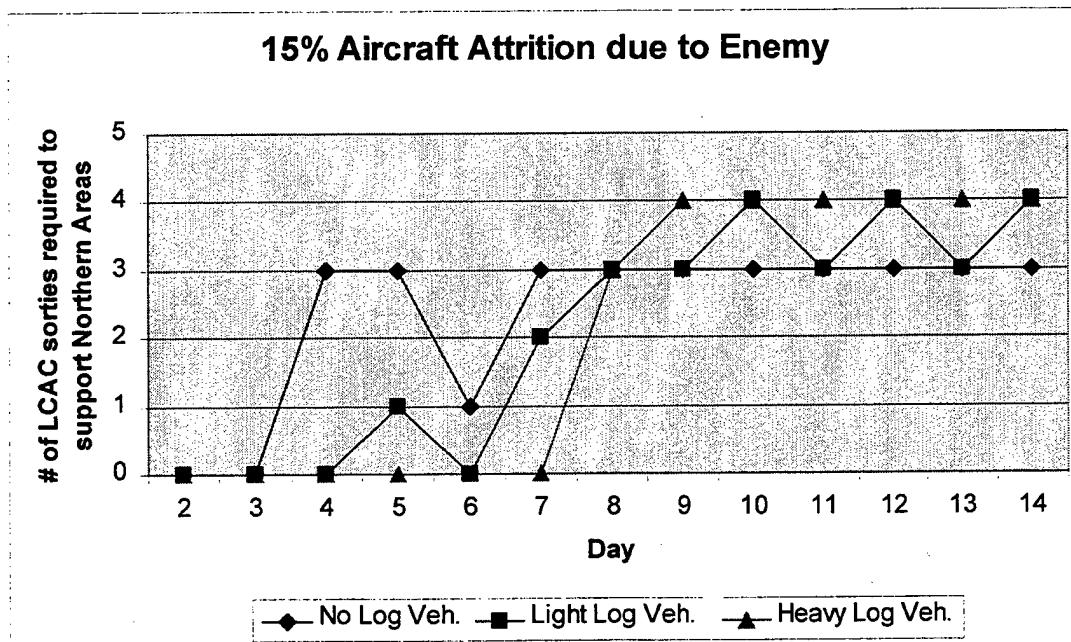

Figure 14. Sea-base #3, LCAC Sorties Required per Day to Support the Northern Areas

After observing all the information presented, planners in this scenario should decide how the following desires rank in importance to the success of the operation:

- Minimize the total number of LCAC sorties required to deliver sustainment to the forces ashore.

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- Minimize the maximum number of daily LCAC sorties delivering sustainment to the forces.

- Maximize the delay of the day on which the first LCAC sortie delivering sustainment takes place.

- Maximize the delay of the day on which the first LCAC sortie delivering sustainment to the northern areas takes place.

This ranking, along with the results previously discussed, will help planners make better informed decisions on the deployment of logistics vehicles while operating from Sea-base #3 in this scenario.

VII. CONCLUSIONS

A. OVERVIEW

OMFTS and STOM seek to reduce the footprint of the landing force by sea-basing command and control, logistics, and some of the fire support functions. Both a reduction in logistical requirements and an increase in unit maneuverability are the results of a reduction in the size of the force ashore. To enable the landing force to maintain the best mobility and maneuverability possible, delivery of sustainment from the sea-base by aircraft is desired. This study provides insight into the ability of aircraft to support the delivery of sustainment ashore by observing the effects of varying ship-to-shore distances, aircraft attrition, and footprint of logistics vehicles initially deployed. Aircraft characteristics modeled included:

- Availability, factoring maintenance readiness, attrition from enemy interdiction, and dedication to other missions;

- Range vs. commodity payload for each aircraft type; and

- Operational time required to complete a sortie per distance traveled and aircraft type.

This study's specific results hold only for scenarios with a similar size of deployed forces, aircraft availability, and ship-to-objective distances. The scenario analyzed by this study was generally composed of a small force ashore (approximately 4,300 personnel compared to a traditional MEB landing force of 17,000 personnel), a large number of transporter aircraft in theater (it is still not certain what number of CH-53s and MV-22s will be able to embark together aboard an LHD/LHA), and moderate ship-to-objective distances (distances a lot less than the 250 nm distance that the Chief of Naval Operations expressed interest in analyzing [Ref. 23]).

This study shows that given the forces ashore and the days of the operation, the ability to deliver all required sustainment to forces ashore with only aircraft is feasible when operating at short to medium ship-to-objective distances, even when attrition of

aircraft is relatively high. When ship-to-objective distances are long, though, the delivery of all required sustainment ashore with only aircraft is not feasible. However, to minimize the total number of LCAC sorties required during the operation and to delay the day of the operation when the first LCAC sortie is required, a decision maker could deploy a footprint of logistics vehicles ashore carrying sustainment. Depending on the size of the footprint, this could start to reduce the landing force' maneuverability but could be viewed as preferred to maintaining security of a beachhead and interior lines of communication to the forces ashore, which are requirements once LCACs start to deliver sustainment.

With a larger decrease in aircraft availability due to higher levels of aircraft attrition, the benefits of deploying logistics vehicles ashore become increasingly less, when observing the difference in the total number of LCAC sorties required and the day on which LCAC delivery of sustainment is first required. This results from the need of forces ashore to consume the inventory of the logistics vehicles sooner together with the logistics vehicles' addition to the sustainment requirements becoming more of a burden earlier in the operation.

Generally, the results show that the factor with the most profound affect upon SBL is the ship-to-objective distance. As the distance increases, there is a decrease in both the amount of payload carried and number of possible sorties accomplished also occurs. An insight gained from observing the effects of these reductions is that ship-to-shore distances have more influence over the feasibility of SBL than the other factors examined.

Looking further into the effect of the ship-to-shore distance upon SBL, it is noted that in this study's scenario, an increase in ship-to-objective distances results in fewer TBFDS mission sorties per CH-53 and thus requires more CH-53s for dedication to this mission. While fewer CH-53s are available for sustainment missions, their utility vis-à-vis the MV-22 increases. This increase is due to a decrease in the MV-22's capability to carry bulk liquids as ship-to-objective distances increase. This is illustrated by observing a CH-53 having both the capability to carry 2,000 gallons of fuel and operate at ship-to-objective distances of 170 nm, 140 nm, and 35 nm, while noting an MV-22 having the capability to carry 500 gallons, 1,000 gallons, and 1,500 gallons of fuel when operating at the same respective distances (see also Table 10, page 33). Prior studies have identified

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water and fuel as the SBL drivers [Ref. 8]. Therefore, when comparing the MV-22's capability to deliver sustainment to the CH-53, the MV-22's delivery capability decreases faster than that of the CH-53 when ship-to-objective distances increase.

B.   RECOMMENDATIONS FOR FURTHER STUDIES

Due to the myopic approach (i.e. solving a series of one day scheduling problems instead of a single 14 day scheduling problem) that this study uses to model the problem, it is suggested that further effort go into the development and modifications of the model in support of a multi-period approach. This would allow the user the flexibility to find an optimal solution when the primary objective is either to minimize total number of LCAC sorties required over the operation or to maximize the delay of the first day LCAC sorties are required.

Planners and decision makers should use both this study's model and the 27 case studies developed to examine scenarios where both the size and composition of the landing force and the number of aircraft in theater at the beginning of the operation differ from this study's scenario. Additionally, continuing attempts should be made to gain insight into the effects that varying other factors (varying ship-to-objective distances, enemy attrition, etc) have upon SBL. More detailed analysis will assist in the ongoing concept development process.

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